Spring 2018

Pesticide drift in the Midwest: 2010-2016

Jessica L. Ricchio
University of Iowa

Follow this and additional works at: https://ir.uiowa.edu/etd
Part of the Occupational Health and Industrial Hygiene Commons

ED_005172C_00001927-00001

PESTICIDE DRIFT IN THE MIDWEST: 2010-2016

by

Jessica L. Ricchio

A thesis submitted in partial fulfillment
of the requirements for the Master of Science
degree in Occupational and Environmental Health (Industrial Hygiene) in the
Graduate College of
The University of Iowa

May 2018

Thesis Supervisor: Associate Professor T. Renée Anthony

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Jessica L. Ricchio

has been approved by the Examining Committee for
the thesis requirement for the Master of Science degree
in Occupational and Environmental Health at the May 2018 graduation.

Thesis Committee:

T. Renée Anthony, Thesis Supervisor

Diane Rohlman

Nathan Fethke

To Mom and Dad, for your unwavering support and love throughout my schooling, and for your continued patience with my thirst for knowledge.

To the teachers and professors throughout my schooling— your guidance has cemented my future, and for that I am truly grateful.

Moreover, to the women in science who have paved the way, for without you, there would be no place for me.

For those who say it will never happen to me:

"When any one asks me how I can best describe my experiences of nearly forty years at sea I merely say uneventful. Of course, there have been Winter gales and storms and fog and the like, but in all my experience I have never been in an accident of any sort worth speaking about. I have seen but one vessel in distress in all my years at sea, a brig, the crew of which was taken off in a small boat in charge of my third officer. I never saw a wreck and have never been wrecked, nor was I ever in any predicament that threatened to end in disaster of any sort. I will say that I cannot imagine any condition which could cause a ship to founder. I cannot conceive of any vital disaster happening to this vessel. Modern shipbuilding has gone beyond that."

Captain E.J. Smith
Captain of the RMS *Titanic*

ACKNOWLEDGEMENTS

I would like to thank my academic advisor, Dr. Renée Anthony for her guidance, wisdom, and understanding throughout obtaining this degree. She is the best advisor a girl could ask for. I would like to thank Jenna Gibbs for her continued support and initial data set. Without her seeking help for data entry, this thesis would not have evolved into what it has. In addition, thank you to Diane Rohlman and Nate Fethke, for their commitment and guidance as committee members.

This thesis would not have been possible without the training grant received from the Centers for Disease Control and Prevention and the National Institute for Occupational Safety and Health. The Great Plains Center for Agricultural Health also provided necessary support for this research.

Last, but certainly not least, thank you to the University of Iowa and the faculty of the Occupational and Environmental Health program. Without their belief in me, I would not have a position at one of the best universities in the country. Moreover, I would not have been able to make the lasting connections that I have. Thank you.

ABSTRACT

Approximately 92% of the land in Iowa, 64% in Indiana, and 27% in Michigan is agricultural farmland. Nearly 77% of farmland in Iowa and Indiana, and 58% of farmland in Michigan, were treated with herbicides in 2012 (USDA). Pesticide drift, or "overspray", is defined as any off-site movement of pesticide during its application. Exposure to this drift has the potential to damage crops and landscaping, kill aquatic animals, and cause DNA damage, cancer, and allergic wheeze in applicators. The Pesticide Bureau of the Iowa Department of Agricultural and Land Stewardship (IDALS), the Indiana State Chemist (ISC), and the Michigan Department of Agriculture and Rural Development (MDARD) investigate complaints of pesticide misuse, including reports of pesticide drift. Individual narrative reports and case summaries are available, but have not been analyzed to identify contributing factors to prevent field, worker, and community exposures; nor has the community at large been surveyed about reporting practices.

The aim of this research was to (1) identify determinants of pesticide drift events in the Midwest, comparing between states; (2) compare state policies; and (3) determine the proportion of events in which applicators did not conform to pesticide label guidance. This examination will provide guidance when developing policies and prevention efforts used to minimize the hazards associated with pesticide drift.

Narrative case reports from IDALS and MDARD, and case summaries from ISC spanning 2010-2016 were analyzed. Narratives and case summaries were converted to trackable data for ease of analysis using Excel. Data analysis includes descriptive

statistics on continuous variables (e.g., distance, wind speed), chi-square tests, and t-tests. Analysis includes: crop damage associations with wind speed by chemical; ratio of human exposures across aerial applications, and associations of distance to target crop and reported plant damage. Key state policies were compared and the responses from a survey concerning the reporting of drift incidents was analyzed. The proportion of cases that violated weather and distance recommendations/label directions for the five most common pesticides in each were analyzed.

Between 2010 and 2015, Iowa received 471 reported drift cases; between 2011 and 2016 Indiana received 391, and between 2014 and 2016 Michigan received 91 reports. The five most common pesticides analyzed for during drift investigations varied between states, but 2,4-D, glyphosate, and atrazine were common to all states. The method of application, (i.e., aerial or land), wind speed, and the intended target crop were significantly associated with drift events across all three states. While Iowa was the only state to contain regulatory language concerning drift to bees or livestock, all states still reported 4 to 5% of cases in which pesticides drifted onto animals. Michigan was the only state to suggest the creation and use of a drift management plan and was the only state requiring applicators to inform neighbors of drift. About 30% of confirmed drift cases involved applications within 7.62 meters of desirable vegetation, and about 40% of applications occurred in wind greater than 4.5 m/s. More education, training, and community involvement are suggested interventions to reduce drift cases.

PUBLIC ABSTRACT

In the U.S. Midwest, some states are composed of over 90% agricultural farmland, and a large portion of that farmland has pesticides applied to it to improve crop yield. Pesticides can be applied by people with backpacks, by tractor, and by helicopters or planes. Pesticides have the potential to drift into neighboring properties; exposing plants, animals, and/or humans. By understanding what might cause pesticide drift, better policies, training programs, and educational materials can be provided.

Iowa, Indiana, and Michigan were chosen as representative Midwestern states based on the proportion of corn and soybeans within their borders in 2012 (Iowa and Indiana planted 75% of agricultural land to corn/soybeans; Michigan 44%). Investigations into pesticide drift complaints were used for this study. This study found that Iowa and Indiana had more cases per year than Michigan, and that overall, 31% of pesticide applications occurred within 25 feet of a neighboring property, and 41% of applications were made when wind was greater than 10 mph. When pesticides were applied via planes and helicopters, damage of surrounding property was more likely. And damage was 1.61 times more likely when pesticides were being applied to corn. Future investigations should consider tracking temperature, relative humidity, and distance to property lines, since recommendations for these factors exist. This information can help shape future pesticide labels. Since some pesticides can be volatile and/or toxic, applying pesticides in conditions that do not cause drift is paramount for the health of the applicators and community members.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER 1: INTRODUCTION

A Brief History on Agriculture

Agriculture is defined as "the science, art or practice of cultivating the soil, producing crops, and raising livestock."[1] Hunters and gatherers populated the landscape thousands of years ago until innovative ancestors began experimenting with planting crops, thus beginning the age of agriculture. Cereal and root crops, such as wheat and corn, were the first crops to emerge in agriculture.[2] Domestication of wild animals likely soon followed. Largescale farming, at least large for the time, allowed for surpluses of food in individual households. Surpluses of food allowed for ancient people to seek tasks outside of the household, moving the evolution of society in the present direction. Civilizations developed as a result, since villages became rooted to one location, allowing for the development of trade routes.

While fire was the first agricultural tool available, handheld tilling tools and irrigation technology followed relatively soon after.[2] As the industrial revolution boomed, so too, did agriculture. Advancements in engineering were a boon to the agriculture sector. While English-born Jethro Tull was responsible for the invention of the first horse-drawn seed drill, many machines were also developed in the United States.[2] The crowning achievement of the Midwest was the creation of the steel plow, and later the tractor, by John Deere in 1837.[2] As the years progressed, genetics became the center of agriculture. Gregor Mendel's pea plant experiments revolutionized both science and agricultural communities. His experiments paved the way for selective breeding of both plants and animals. Selective breeding was practiced by everyone from the Mongols to the English, for various purposes of course, but with the goal of retaining desirable livestock traits.[2]

Production truly skyrocketed once science took hold in the sector. By the late 1950s gasoline and electricity powered machinery was being used in almost every stage of farm management.[2] Over time, genetic modification of plants became essential to the sustainability of agriculture. The father of the "green revolution," Norman Borlaug, created high-yielding disease-resistant wheat, and its subsequent introduction into densely populated countries like Mexico and India provided a larger and more sustainable food source to address the population crisis of the mid-1900s.[3] Higher yields have resulted from combining the DNA of different species of plants, for example combining Arctic plant DNA with strawberry plant DNA to allow for growth of strawberries in colder climates, thus allowing for their survival in harsher conditions.[2]

These innovations, have allowed agriculture to flourish across the globe. In particular, the Corn Belt, located in the Midwest U.S., produces most of our nation's corn. Although very little of the corn grown in this location is for human consumption, the scope of production and the speed of planting and harvesting would not have been possible without the innovations over the last several thousand years. One of the more controversial advancements in agriculture is the use of pesticides.

Pesticides in Agriculture

The U.S. Environmental Protection Agency (EPA) defines a pesticide as "any substance…intended for preventing, destroying, repelling, or mitigating any pest".[4] Pesticides used today in agriculture are categorized broadly as herbicides, insecticides, or fungicides, which are used to repel weeds, insects, and fungus respectively. Pest repellants are not a new concept. In 2500 BCE, the Sumerians were documented to have rubbed sulfurous compounds on their skin to control insects and mites and the Chinese are documented to have erected bamboo "bridges" between citrus trees to allow predatory ants to travel among the grove, protecting the trees from caterpillars and beetles.[5]

Crop protection, the protection of plants from disease, weeds, and pests, became a concern in the early 1800s, and as a result, pesticides became much more prevalent in agriculture.[5] Farmers began applying pesticides aerially in 1921 to cover more cropland; increasing crop yield led to increasing profit margins.[5] Aerial applications and new machinery allowed for faster pesticide applications and more land coverage. Covering more cropland meant larger acreages could be planted, treated, and harvested. However, larger acreage also means a larger opportunity for error in terms of over application, occupational and community exposure, and environmental contamination.

In 1939 a pesticide was created that would earn its creator a Nobel Prize—dichlorodiphenyltrichloroethane (DDT).[5] Although considered a miracle mixture, within a few decades scientific opinion shifted. Scientists discovered that organochlorine pesticides, including DDT, were bio-accumulating in the food chain.[5] DDT began to accumulate in the fat of predatory animals, such as eagles, as they consumed the primary and secondary predators of target pests; this accumulation caused fragile and deformed eggs in predatory birds.[5] The banning of DDT in the 1970s prompted the creation of "new organic chemical pesticides that would change agriculture" and the future of responsible farming practices.[5]

Modern integrated pest management (IPM) entered the agricultural sector before DDT was banned and continues to be an important theory today. Integrated pest management operates under the assumption that infestations should be *managed* and not simply *eradicated*.[5] Integrated pest management requires knowledge of ecological principles, pest life cycles, and pest population behavior, which can discourage some people from practicing it.[5] In the 1990's bio-rationals were introduced— pesticides that use naturally occurring hormones, microbes, venoms, or extracts as the basis for synthetically produced pesticides.[5] Other pesticides that are on the market include herbicides, insecticides, fungicides, and rodenticides, which are used to discourage weeds, insects, funguses, and rodents respectively. Although the EPA regulates all pesticides in the U.S., individual states can also require the registration of pesticides used. Common pesticide exposures occur while mixing, loading, and applying pesticides, and contacting treated plants and soil, or ingesting contaminated fruits and vegetables.

Midwest Pesticide Use

Among the states of Iowa, Indiana and Michigan, the pesticides most commonly involved in pesticide drift events are: 2,4-dichlorophenoxyacetic acid (2,4-D), acetochlor, atrazine, glyphosate, pyraclostrobin, metolachlor, saflufenacil, prothioconazole, and tebuconazole. 2,4-D, acetochlor, atrazine, glyphosate, metolachlor, and saflufenacil are herbicides, while pyraclostrobin, prothioconazole, and tebuconazole are fungicides. This is important because herbicide damage is easily noticeable on surrounding plants. Fungicide damage is hard to determine because it does not affect plants. The same goes for insecticides; since plant damage is not a result of exposure, it is hard to determine if accidental exposure has occurred. Insecticides also have the ability to harm humans because it attacks the central nervous system of living animals, not plant material.

Between these states, a total of 55.3 million acres of crops were harvested in 2012; of those harvested acres, 22.1 million acres were corn and 16.4 million acres were soybeans.[6-11] Table 1 provides a summary of the type and amount of the most common pesticides applied to corn and soybeans across Iowa, Indiana, and Michigan. In several cases the pounds applied was not available to protect individual operations from identification. Corn had seven times the amount of pesticides applied to it compared to soybeans, even though there was only 1.4 times the amount of corn planted. The pesticides listed in Table 1 below were selected because they were some of the five most common pesticides involved in drift events in each of the three states.

Table 1. Millions of pounds of pesticide applied to soybeans (2015) and corn (2016) across Iowa, Indiana, and Michigan.[12, 13]

Pesticide	Soybeans	Corn
2,4-D	1.10	0.70
Acetochlor	0.54	11.7
Atrazine	-	13.7
Glyphosate	1.90	2.3
Pyraclostrobin	0.10	0.26
Metolachlor	1.60	6.8
Saflufenacil	0.05	-
Prothioconazole	-	-
Tebuconazole	-	-

Pesticide Descriptions

The history, use, and physical properties of the nine pesticides most commonly involved in pesticide drift events examined in this three-state region are detailed in this section. Table 2 summarizes the specific human health effects for each pesticide.

Table 2. Potential health effects of the five most common pesticides involved in pesticide drift cases in Iowa, Indiana, and Michigan.

Pesticide	Potential Health Effects Central Nervous	Respiratory	Circulatory	Skin/Eye Irritant	Reproduction	Cancer
2,4-D	+		+			Possibly
Acetochlor		+		+	+	Likely
Atrazine			+		+	No
Glyphosate				+		Probably
Pyraclostrobin				+		No
Metolachlor	+	+	+	+		Possible
Saflufenacil			+	+	+	No
Prothioconazole			+		+	No
Tebuconazole					+	Possible

References: [14-22]

2,4-D

2,4-D (CAS# 94-75-7; Derivatives: 2702-72-9, 5742-19-8, 2008-39-1, 5742-17-6, 32341-80-3, 1929-73-3, 1928-43-4, and 94-11-1) is a synthetic herbicide, with nine variations that are sold as both a powder and a liquid that is applied both aerially and by land.[14] It was first used in the U.S. in the 1940s and was an ingredient in Agent Orange, which was used during the Vietnam War.[23] The half-life of 2,4-D is 19 hours in air, and it takes between 6 and 333 days to breakdown in soil or water depending on the aerobic conditions.[14] Environmentally, some forms are toxic to plants, fish, and other aquatic organisms; it is non-toxic to moderately toxic to birds; and non-toxic to honey bees and other beneficial insects.[23]

Routes of exposure include ingestion, injection, and dermal; the amount of 2,4-D that can enter via the lungs has not been determined at this time.[14] The herbicide 2,4-D can be found in all organs of the body, however it is not metabolized and, as a result, it is usually excreted via urine within 24 hours.[14] Harmful effects are only seen when individuals ingest large amounts of the herbicide. Few human studies support the hypothesis that exposure to 2,4-D can lead to cancer, although some studies have found weak links between exposure and cancers of the lymphatic system.[14] The International Agency for Research on Cancer (IARC) has classified 2,4-D as a Group 2B carcinogen, which means 2,4-D is "possibly carcinogenic to humans," but there is a lack of human evidence and only limited animal evidence available.[14]

The herbicide 2,4-D is regulated by the EPA, Occupational Safety and Health Administration (OSHA), and the Food and Drug Administration (FDA), with exposure limits also recommended by the National Institute of Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH). Exposure limits are as follows: 1 mg/L in water for a 22 pound child (EPA), 10 mg/m^3 8-hr time-weighted average (TWA) (OSHA), 0.07 mg/L of bottled water (FDA), 10 mg/m^3 10-hr TWA (NIOSH), and 10 mg/m^3 TWA (ACGIH).[14]

Acetochlor

Acetochlor (CAS# 34256-82-1) is an herbicide applied most often before planting of corn; it can only be applied using land equipment. It was registered with the EPA in 1994, when it was introduced to control grasses, broadleaf weeds, and yellow nutsedge.[24, 25] Depending on the target crop, different allowable tolerances exist, which range from 0.05 parts per million (ppm) for field grain corn, popcorn grain, sweet corn kernels, and sorghum grain to 4.5 ppm for forage field corn.[26] The main degradation pathway is microbial; persistence in the environment ranges from 8-12 weeks depending on soil type and climate.[25]

After exposure, 80% of acetochlor will be absorbed into well-perfused organs, such as the kidneys and the liver, within 48 hours and it has low potential for bioaccumulation.[27] The majority of acetochlor is eliminated from the body via urine, with 66-72% of the volume exiting the urethra and 12-21% eliminated via the feces.[27] Acetochlor is irritating to both the respiratory system and the skin.[27] Environmentally, acetochlor can be toxic to targeted pests and fish and moderately toxic to honeybees; low toxicity was observed in birds.[25, 28]

Acetochlor lacks occupational exposure limits. Maine and Minnesota have established drinking water standards at 14 mg/m^3 and 9 mg/m^3 respectively.[29] The EPA "has determined there is a reasonable certainty no harm will result from aggregate non-occupational exposure."[30] Although the EPA has declared no harm will result to the community, in 2007 acetochlor was classified as "likely to be carcinogenic to humans" due to the "suggestive evidence of carcinogenic potential."[31] This difference is due to potential exposure. It is very unlikely that community members contact acetochlor during application, but applicators are at a much greater risk of both exposure and at exposure for a longer time.

Atrazine

Atrazine (CAS# 1912-24-9) is an herbicide used for pre- and post-emergent control of broadleaf weeds in crops and evergreen forest regrowth.[16] Atrazine was first registered as an herbicide in 1958, with use restricted to allow only certified applicators to apply atrazine to crops in a powder, droplet, or granular form using land or aerial equipment.[16, 32] Applied in the spring and summer, atrazine must first dissolve during a rain event to facilitate uptake in surrounding plants.[16] The half-life of atrazine in air is 14 hours when hydroxyl radicals are present; it is greater than 200 days in water columns of lakes and streams; and it ranges from 14 to 109 days (mean = 39 days) in soil.[16]

Although atrazine is persistent in the environment, it does not seem to bioaccumulate nor biomagnify in the food chain.[16]

Atrazine can persist in groundwater, which means drinking from contaminated wells is an exposure pathway for the community. The amount absorbed when atrazine is inhaled is unknown, only a small amount is absorbed after dermal exposure, and the majority of ingested atrazine will enter the bloodstream.[16] Metabolites of atrazine may enter lipid layers or organs, but they do not accumulate in the human body; the majority of metabolites are excreted within 24-48 hours in the urine and feces.[16]

Human studies on health outcomes after exposure are rather limited. Currently, there is a lack of human and animal data to support a cancer link. Some studies have proven associations between mammary tumors in rats and atrazine exposure, other studies have not found an association; therefore the IARC has determined that atrazine carcinogenicity is a Group 3 carcinogen, which is "not classifiable" as a human carcinogen "based on inadequate evidence in humans and sufficient evidence in experimental animals."[16] Environmentally, atrazine is slightly toxic to birds and aquatic animals and is non-toxic to bees; fish have a low level of bioaccumulation.[28, 33] As for federal regulations, several agencies have provided guidance to employers. OSHA has a 5 mg/m^3 8-hr TWA; NIOSH has a 5 mg/m^3 10-hr TWA; ACGIH has recommended a 2 mg/m^3 TWA, and both the FDA and the EPA have set maximum contaminant level allowed in drinking water at 3 mg/m^3.[16]

Glyphosate

Glyphosate (CAS# 1071-83-6) is an herbicide registered with the EPA in 1986, although it has been in use since the 1970s and is used to kill broadleaf plants and grasses and to regulate plant growth and ripen fruit.[17] It can be applied using land or aerial equipment, but aerial equipment is only allowed in pre-harvest situations. A non-selective herbicide, it prevents plants from synthesizing required proteins needed for plant growth.[17] Microbes are responsible for breakdown in soil and water; the half-life ranges from 1 to 174 days in soil and 12 to 70 days in pond water.[34] While it can persist in soil for up to 6 months, it does not enter groundwater easily because glyphosate binds tightly to soil.[17] One study concluded that less than 2% of applied glyphosate was found in run-off.[35]

Within 72 hours, 90% of glyphosate that is absorbed dermally or ingested will pass through the body; the vast majority is excreted un-metabolized in urine (30%) or feces (70%), with less than 0.5% remaining in tissues and organs.[36] In 2015 the IARC classified glyphosate as a Group 2A carcinogen, "probably carcinogenic to humans" due to sufficient animal evidence and limited data in humans linking exposure to non-Hodgkin's lymphoma.[37] Environmentally, glyphosate is slightly toxic to birds, but non-toxic to fish and honeybees, with a very low potential for bioaccumulation in fish.[35, 38] As of December 2017, no U.S. federal agency has established an exposure limit. In June 2017, California made the step to curtail glyphosate use based on recent cancer studies. Monsanto, the largest manufacturer and distributor of glyphosate, is taking legal actions as a response.

Pyraclostrobin

Pyraclostrobin (CAS# 175013-18-0) is a fungicide registered with the EPA in 2007 that can be applied both aerially or by using land equipment. Although it can be highly toxic to fish, it is only toxic to birds and mammals after chronic exposure.[39]

Pyraclostrobin is relatively immobile in soil, with a half-life of 3-82 days depending on whether it is an anaerobic or aerobic condition.[39] The half-life in water is only two hours.[39] Only half of the original dose is retained when ingested, with rapid metabolization and excretion of the dose via urine (10-15%) and feces (33%) occurring soon after ingestion by rats.[36] In 2007, pyraclostrobin was classified as "not likely to be carcinogenic to humans" due to inadequate data.[31] No federal or state exposure limits or recommendations exist as of December 2017.

Metolachlor

Metolachlor (CAS# 51218-45-2) is an herbicide that is now used for pre-emergent control of broadleaf and grassy weeds in corn, soybeans and other food crops, but it was originally registered with the EPA in 1976 for use in non-crop areas.[40, 41] It can be applied using both aerial and land equipment. The half-life of metolachlor in water ranges from 97 to 200 days depending on acidity and ranges between 15 and 50 days in the soil, but degradation largely depends on present microorganisms, temperature, and water content.[42, 43] Metolachlor has been found in well water samples within the community, offering a potential pathway of exposure for non-applicators.[44]

Since ingested metolachlor is quickly metabolized and 70-90% is excreted in the urine and feces within 48 hours, it is not bioaccumulated or biomagnified in organisms; metolachlor itself is not detectable in excretions or tissues, but metabolites have been found in trace amounts in organs and blood.[19, 41] Research using rats has indicated that teratogenic, developmental, and mutagenic effects in humans are unlikely at anticipated exposure levels.[19, 43, 45, 46] In 1991, the EPA recommended a carcinogenicity classification of Group C, "possible human carcinogen," due to the increase of liver tumors in female rats.[40] Ecologically, metolachlor is non-toxic to birds and bees and moderately toxic to fish; very little metolachlor is bioaccumulated in fish.[43] The federal drinking water guideline provided by the EPA is 700 mg/m^3; state drinking water guidelines range between 15 mg/m^3 and 800 mg/m^3.[29] No federal or state exposure limits or recommendations exist as of February 2018.

Saflufenacil

Saflufenacil (CAS# 372137-35-4) is an herbicide used for pre-emergent control of weedy grasses in a variety of food crops; it was first registered with the EPA in 2009.[47] It can be applied both aerially and by land, however no aerial applications are allowed in California. The half-life of saflufenacil in soil ranges from one to five weeks and it persists in water for less than one week up to ten weeks depending on the acidity level.[20] Saflufenacil must be applied to cropland before planting or after harvesting. Studies using rats indicated that the majority of saflufenacil is eliminated within the first 24 to 48 hours, with complete elimination by 96 hours; male rats eliminated more saflufenacil via the feces, while female rats eliminated more via urine.[20] Remaining parent molecules and metabolites were found in very low concentrations in the muscles, liver and skin; there is a low risk of bioaccumulation.[20]

Saflufenacil is currently classified as “not likely carcinogenic to humans” due to lack of studies proving an increase in tumors after exposure.[20] Saflufenacil is non-toxic to fish, birds, and non-target terrestrial insects.[20] As of December 2017, there are no federal, state, or agency regulations and/or recommendations for exposure limits.

Prothioconazole

Prothioconazole (CAS#178928-70-6) is a fungicide first introduced in 2002, used for pre- and post-emergent control of a variety of diseases in cereal grains.[48] It can be applied using aerial or land equipment. When in vapor phase, hydroxyl radicals provide a half-life in air of 3.4 hours.[49] In acidic waters, prothioconazole has a half-life of 120 days, however anaerobic half-lives in sediment rich environments range from 62 to 231 days.[50] In loamy soils, the half-life can range between 533 and 1336 days, which indicates that biodegradation in soil is not an important method of removal.[50]

Prothioconazole has low bioaccumulation potential; approximately 94-95% of administered doses in rats was recovered.[21] The primary route of excretion for both male and female rats is via feces, 84% and 78% respectively; approximately 90% of the dose is eliminated within 24 to 48 hours.[21] Studies have found that prothioconazole has low toxicity via oral, dermal, and inhalation routes, but target organs do include the liver, kidney, and thyroid.[21] Prothioconazole is considered "not likely to be carcinogenic to humans." Environmentally, prothioconazole is not toxic to birds and moderately toxic to fish, aquatic invertebrates, and honeybees.[48] Allowable tolerances on crops range from 0.15 ppm for soybean seeds to 17 ppm for soybean hay according to the EPA, however no federal or state occupational exposure limits exist as of March 2018.[48, 51]

Tebuconazole

Tebuconazole (CAS# 107534-96-3) is a fungicide used to control for diseases in cereal and other field crops and it was first introduced in 1986.[22] It can be applied using land or aerial equipment. Tebuconazole has a half-life of 49 to 122 days in soil, making it relatively persistent; it has little potential to reach groundwater sources, but its mobility in soil increases as the organic material content decreases.[52] In pH neutral water, tebuconazole has a calculated half-life of 590 days.[52] Research has indicated that there is low potential for bioaccumulation magnification within the food chain; only 0.21 to 0.67% of original doses have been found in rat tissues.[52, 53]

Absorption via dermal contact is relatively low, 37% or less of applied tebuconazole is absorbed within 24 hours.[54] Within 72 hours, excretion of tebuconazole ranges from 91 to 98%; male rats excreted 77 to 80% of the dose through feces, while females excreted only 60 to 67% through feces.[53] Tebuconazole is a Group C carcinogen—"possible human carcinogen."[22, 31] Environmentally, there is no acute risk posed to fish, birds, and small mammals, but a chronic risk to fish and birds that eat grasses and insects is present; honeybees face a low to moderate risk.[22, 52] No federal or state regulations or recommendations exist as of March 2018, however FIFRA tolerances range from 0.05 ppm for wheat grains to 55 ppm for grass seeds.[51]

Pesticide Use by State

Iowa, Indiana, and Michigan differ in terms of population and agriculture. The state of Michigan contains the largest population of the three states with 10 million people; Indiana's population is 6.7 million and Iowa's population is 3.1 million.[55-57] In terms of farmland, the opposite is true. Iowa contains the most farmland at 30.6 million acres, Indiana has 14.7 million acres, and Michigan has nearly 10 million acres.[6-8] The three most planted crops in the state of Iowa are corn (45%), soybeans (30%), and oats (0.2%).[9] Indiana's top three include corn (41%), soybeans (35%), and wheat (2%).[10] And Michigan's largest agricultural contributions include corn (24%), soybeans (20%), and wheat (5%).[11] All three states' biggest cash crops are corn and soybeans. The proportion of corn and soybeans, led to choosing these specific states. In 2012, roughly 75% of all available farmland in Iowa and Indiana was planted to row crops such as corn and soybeans; only 44% of farmland was planted to row crops in Michigan. In Iowa, the five most common pesticides analyzed for during drift investigations include 2,4-D, acetochlor, atrazine, glyphosate, and pyraclostrobin. The five most common pesticides in Indiana by contrast are 2,4-D, atrazine, glyphosate, metolachlor, and saflufenacil. And in Michigan the five most common pesticides are 2,4-D, atrazine, glyphosate, metolachlor, prothioconazole, and tebuconazole (the last three tied for 4th and 5th most common in Michigan). All three states had 2,4-D, atrazine, and glyphosate as some of the most common pesticides involved in drift events.

Exposure Regulations and Recommendations

International, federal, and state agencies and regulatory bodies approve and track pesticide use and/or exposure, for both people and the environment. Internationally, the IARC evaluates whether substances are carcinogenic to humans, and the World Health Organization establishes international air and drinking water guidelines. The U.S. EPA has the authority to regulate pesticide sale, use, and distribution in the United States under the Federal Insecticide, Fungicide, and Rodenticide Act of 1996. The EPA, the Bureau of Land Management, and the U.S. Fish and Wildlife Service assess the risks pesticides pose to ecosystems. The FDA and the United States Department of Agriculture (USDA) help to ensure low concentrations of pesticides in food. For occupational exposure recommendations and regulations, the ACGIH, the American Industrial Hygiene Association (AIHA), the Department of Energy, NIOSH, and OSHA provide information to employers and workers on exposures to harmful substances.

States also have the ability, in some cases, to provide exposure limits if they are stricter than current federal regulations.

Table 1, below, lists the most common pesticides analyzed for in the states of Iowa, Indiana, and Michigan during pesticide drift investigations and other respective regulatory and recommended exposure limits. The air concentrations provided by OSHA and the water concentrations provided by the EPA and FDA are federal regulatory limits; the air concentrations provided by NIOSH and the ACGIH are agency recommendations. Of the nine pesticides only 2,4-D, atrazine, and metolachlor have exposure regulations or recommendations. Acetochlor, glyphosate, pyraclostrobin, saflufenacil, prothioconazole, and tebuconazole each lack regulations and recommendations for airborne occupational exposure and public drinking water concentrations.

Table 3. Regulatory and recommended exposure guidelines for the most common pesticides in the states of Iowa, Indiana, and Michigan (mg/m^3).

	Air OSHA*	Air NIOSH†	Air ACGIH	H_2O EPA‡	H_2O FDA$^{\alpha}$
2,4-D	10	10	10	1000	70
Acetochlor	-	-	-	-	-
Atrazine	5	5	2	3	3
Glyphosate	-	-	-	-	-
Pyraclostrobin	-	-	-	-	-
Metolachlor	-	-	-	700	15
Saflufenacil	-	-	-	-	-
Prothioconazole	-	-	-	-	-
Tebuconazole	-	-	-	-	-

*8-hour time-weighted average
†10-hour time-weighted average
‡Drinking water for a 10kg child
$^{\alpha}$Bottled water

Environment and Human Health Effects

The Environment: Degradation and Buffer Zones

One of the first steps in determining how hazardous a pesticide is to the environment is determining its ability to degrade in soil. Pesticides that are highly toxic and persist in soil will have a more deleterious effect than less toxic, less persistent, pesticides. In the late 1990s, Australian research on the degradation rates of eight different pesticides (chlorpyriphos, chlorthal dimethyl, fenamiphos and metabolites, linuron, metalaxyl, metribuzin, prometryne, and propyzamide) was conducted in both laboratory and field settings. While the half-lives ranged from 23-142 days, four pesticides persisted longer in surface soil (chlorpyriphos, chlorthal dimethyl, linuron, and propyzamide) (and four persisted longer in deeper soil strata (fenamiphos, metalaxyl, metribuzin, and prometryne)).[58] Understanding degradation rates in soil can help determine potential groundwater contamination after application.

Another aspect of environmental risk to consider is the potential impact on flora and fauna. Studies from the Netherlands have found that a 3-6 meter buffer zone, composed of no crops or unsprayed crops, allows for more diverse vegetation to grow adjacent to the field.[59] Application tanks usually contain a mixture of multiple active ingredients, all of which might have a different preferred buffer zone. A Belgian study found that pesticide drift was not a risk to earthworms or bystanders, however introducing a buffer zone protected aquatic organisms.[60]

Buffer zones benefit non-target fauna that might inhabit the area near crop acreage. A Turkish study found that acetochlor posed the highest risk to aquatic organisms, and that a 57-meter buffer zone was required when farming sunflowers, but no buffer zone around corn was necessary to protect aquatic organisms.[61] Another study from the Netherlands identified that the distance a pesticide drifted into a ditch increased from 0% to 7.2% when winds increased from 0.45 m/s to 4.9 m/s.[62] This same study also found that the bigger a buffer zone, the less drift entered into outlying areas. A 3-meter buffer zone yielded a 95% reduction of drift into the ditch and; a 6-meter buffer zone yielded a 100% reduction of drift into the ditch.[62]

Human Health Effects and Exposure

Exposure to pesticides can often lead to acute and chronic health effects for those exposed. The U.S. based Agricultural Health Study (AHS) found that 7% of pesticide applicators had one or more hospital visits as the result of an occupational exposure to pesticides.[63] Hospital visits were almost twice as likely for commercial applicators, who were more likely to seek care when they were exposed to pesticides while mixing their own pesticides and personally maintained their own equipment.[63] Applicators who were females or high school graduates were less likely to seek medical care.[63]

Another U.S. study using the Sentinel Event Notification System for Occupational Risk (SENSOR) program data discovered that pesticide drift incidence rates were the highest for applicators 20-24 years old compared to other age groups and that 70% of hospital visits post-drift were low severity, with only 0.4% considered high severity; three fatalities however, were identified.[64] This research also found that agricultural sectors had a drift incidence rate of 18 cases per 100,000 people, while non-agricultural sectors had a drift incidence rate of only 0.53 drift cases per 100,000.[64] Insecticides accounted for 49% of all illnesses after exposure to drift.[64] Since insecticides are odorless, tasteless, and do not damage foliage, it is much harder to associate an health/environmental outcomes with exposure to insecticides due to no obvious signs of misapplication or accidental exposure.

Numerous studies have explored chronic health effects of pesticide exposure. A study using data from the AHS determined that 74% of applicators reported at least one episode of rhinitis (i.e., inflammation of nose mucosa) in the previous year, with 2,4-D and glyphosate significantly associated with current rhinitis when both were used in the past year.[65] A study from Mexico reported that 20% of the exposed group showed organ system alterations and free DNA fragments in plasma.[66] Another U.S. study determined that 19 pesticides were significantly associated with self-reported allergic wheeze and that both glyphosate and 2,4-D showed evidence of exposure-response relationships.[67]

In general, many studies of occupational pesticide exposure focus on cancer and other DNA alterations. DNA alternation can begin before birth, according to one Brazilian study that linked maternal farming during pregnancy with larger anogenital distance and testis volume in male offspring.[68] When considering telomere length, a U.S. study using data from the AHS found that lifetime use of 2,4-D has been significantly associated with shorter relative telomere length.[69] Telomere length is directly associated with cell life span. As telomeres shorten, DNA is in danger of being damaged; after telomeres reach a critical length cells can no longer divide and begin to die off. One Mexican study determined the presence of marked DNA damage in aerial applicators with as little as two years of experience in the industry.[70] Acetochlor, one of the most common pesticides used by this study population, has been significantly associated with lung cancer and colon cancer (1.74 and 1.75x more likely respectively) based on AHS data.[71] Increased risk of leukemia in Italian orchard workers has been associated with herbicide use for both males and females, and with insecticide use for just females; there is also evidence that non-Hodgkin's lymphoma is significantly associated with exposure to 2,4-D.[72]

Pesticide Drift

Pesticide drift is defined by the EPA as "movement of pesticide dust or droplets through the air at the time of application…to any site other than the area intended."[73] Exposure to pesticides, even via drift, can have an effect on humans and desirable vegetation. Some people experience respiratory distress or skin irritation when exposed, while crops, trees, and flowers can become damaged, made unusable, or die off. The EPA maintains a Pesticide Drift Reduction Technology (DRT) voluntary program, which encourages the manufacture and use of spray technology/equipment that has been scientifically proven to reduce the incidence of drift events.[74] The new method/equipment is then evaluated and graded by the EPA (one to four stars) based on its potential drift reduction capabilities; the star ratings range from 25-50% to greater than 90% reduction in drift.[74, 75]

Many variables need to be considered when trying to understand pesticide drift including: weather patterns, season, land use, equipment, and topography. Outdoor herbicide concentrations were greater in winter, while insecticide concentrations were greater in autumn; no differences between rural and urban air concentrations was observed.[76, 77] A Scandinavian study found that while personal homeowner exposure was poorly associated with application of 2,4-D, 68% of exposure variation in occupational application of 2,4-D was explained by nozzle type and personal protective equipment (PPE) used.[78]

Much of the community exposure data available evaluates home exposures near agricultural areas. In 2006, one study attempted to determine the association between crop proximity and pesticide concentrations in homes in Iowa. Results indicated that 58% of study participants lived within 500 meters of row crops.[79] If the home was within 750 meters of cropland, increasing acreage of crops increased the likelihood of finding herbicides in the home.[79] This study also detected 2,4-D in 95% of all cases studied. A meta-analysis evaluating non-occupational pesticide exposure pathways for U.S. women living in agricultural areas found an association between pesticide drift and increased levels of pesticide dust concentrations and biomarker levels.[80] Only one U.S. study has attempted to determine the characteristics and outcomes of pesticide drift to the community from agricultural applications. The authors used SENSOR program data and reported that 92% of human exposure to pesticide drift experienced a low-level illness and that 14% of drift exposure cases were children.[81] Soil applications and fumigants caused most of these exposures, and aerial applications accounted for 24% of all exposures.[81] The most common characteristics associated with drift cases in this study included weather, improper sealing of a fumigation site, and applicator carelessness.[81]

The equipment used to apply pesticides may affect both exposure to the applicator and whether the pesticide drifts out of the target application area. Types of equipment used most commonly in the U.S. Midwest include UTVs with attached sprayers, tractor booms, planes, and helicopters. Each method requires different considerations for a successful application, and each application method will limit the amount and type of pesticide being applied. Drift deposition from a backpack spraying evaluation at a USDA Forest Service facility in Missoula, Montana was measured as 1% of the application rate at 1.5 meters downwind from the spray location.[82] Using utility task vehicles (UTVs) to spray resulted in drift deposition between 0.1 and 50% of the application rate.[82] When looking at drift distances of 2.5 meters, the deposition rate ranged from 0.01 to 2% of the application rate for UTV spraying.[82] As the distance increases, the amount of drift deposition decreases.

Outside of learning about PPE usage, learning about exposure pathways allows for the creation of prevention strategies. In Australia, a nationwide survey of more than 10,000 citizens indicated that 4% had occupational pesticide exposure histories.[83] Exposure was more likely among male natural born citizens living in remote areas with low levels of education; glyphosate was the most common pesticide applied.[83] A 2010 U.S. study on the association between occupational pesticide exposure and urinary biomarkers reported that 2,4-D biomarker levels were highest in the spring; seasonable variability accounted for 84% of the total variation in drift models.[84] Workers cannot control the season in which they have to spray certain pesticides, however they can, in most cases, control their spray equipment, PPE used, and spray techniques. Another U.S. study used the AHS participants to characterize the variables affecting exposure. In this case, the differences in 2,4-D concentrations measurements were due to application methods, glove use, repair level of equipment, duration of use, and contact with treated vegetation.[85]

Key Motivation and Goals

There are several gaps in knowledge concerning pesticide drift in the Midwest. Many studies concerning pesticides focus on the acute and chronic health effects of exposure. Additionally, many studies also address exposure pathways, however, those studies typically focus on take-home or occupational exposures. Only one study addressed pesticide drift and its characteristics in the United States, with only two sets of data coming from Midwestern states (Iowa and Michigan).[64] The majority of studies examining pesticide drift exposure pathways and health effects are conducted in European or South American countries. Weather conditions, pesticides, equipment, spray techniques, and crops/production levels are vastly different in these settings compared to the U.S. Midwest. This thesis attempts to fill the gap in understanding how pesticide drift occurs in the Midwest, identify the scope of the case history to the affected communities, and to characterize how drift affects the people and crops within the Midwest. By addressing this gap, an evidence based approach to policies and prevention efforts can be recommended. This thesis will also provide a blueprint for analysis of community reported pesticide drift reports.

Therefore, the goals of this thesis are as follows: 1) examine determinants of pesticide drift events in the Midwest, comparing between states; 2) compare state pesticide regulations; and 3) determine the proportion of events in which applicators did not conform to pesticide label guidance.

CHAPTER 2: PESTICIDE DRIFT IN THE MIDWEST: 2010-2016

Introduction

In the U.S. Midwest, agriculture contributed 137 billion dollars to the U.S. GDP (about 1%) in 2015, with pesticides applied to 436 million acres in 2012. Pesticides used in today's agriculture are categorized broadly as herbicides, insecticides, or fungicides, which are used to repel weeds, insects, and fungus, respectively. In Iowa, Indiana, and Michigan, 55.3 million acres of crops were harvested in 2012; of those harvested acres, 22.1 million acres were corn and 16.4 million acres were soybeans; corn and soybeans were the biggest cash crops in each state.[6-11] Pesticide applications for these row crops use either land equipment, typically via sprayers from tanks connected to tractors, or aerial equipment, which include airplanes and helicopters. During applications, pesticides can drift to areas other than the area intended for treatment.[73] Exposure to pesticides, even via drift, can effect both humans and desirable vegetation. Some people experience respiratory distress or skin irritation when exposed, while crops, trees, and flowers can become damaged, made unusable, or die off when exposed to herbicides.[86]

This study identified the extent of pesticide drift in the Midwest by examining reported cases of drift within affected communities, and characterizing how drift affected the people and crops within Iowa, Indiana, and Michigan. Data for this analysis were extracted from community reported pesticide drift events, as reported to agencies in three Midwestern states. These data were examined to identify (1) determinants of pesticide drift events in the Midwest, comparing between states; (2) compare state policies; and (3) determine the proportion of events in which applicators do not conform to pesticide label guidance. This examination will provide evidence to develop policies and prevention efforts to minimize the hazards associated with pesticide drift.

Materials and Methods

Selection of Midwest States

Iowa, Indiana, and Michigan were selected based on the proportion of row crops within their borders. In 2012, row crops, such as corn and soybeans, were planted on 75% of the available farmland in Iowa and Indiana. In Michigan, however, row crops were only planted on 44% of available farmland in 2012. Iowa and Indiana were selected to represent more row crop intensive states, which are more commonly found in the Midwest, while Michigan was ultimately selected to represent states with a wider variety of agricultural production, and therefore less row crops. State pesticide regulations are not universal, which means state regulations differ based on the needs and practices of the agricultural community. All regulations pertaining to pesticide registration and application in each state were read and compared to each other to examine the possible impact of these regulations on pesticide drift reporting.

Data Collection

Reported cases were obtained from the Pesticide Bureau of the Iowa Department of Agricultural and Land Stewardship (IDALS), the Indiana State Chemist (ISC), and the Michigan Department of Agriculture and Rural Development (MDARD). Data were available from 2010-2015 (Iowa), 2011-2016 (Indiana), and 2014-2016 (Michigan). Freedom of Information Act requests were submitted to both Iowa and Michigan departments; Indiana's cases were available for viewing online. This study was submitted, considered, and approved by the University of Iowa's Institutional Review Board (201707822).

Cases were identified by IDALS, ISC, and MDARD after complaints of perceived pesticide drift were received; only cases in which a full investigation was performed were included. A "confirmed drift" case was defined when the governing agency determined a drift incident had occurred; a "confirmed non-drift" case was defined as either a case in which the governing agency had determined a drift incident had not occurred, or in which the alleged pesticide drift was in actuality a fertilizer, ammonia, or cover crop application. Data analyses for this study were restricted to "confirmed drift" and "confirmed not-drift" cases in the state records.

Case narratives were reviewed to identify the following variables: confirmed status of the drift; month, time of day, and season of application; county and rurality; distance from the application field to a complainant's house and vegetation; method of application; intended use of pesticides; desired target crop; vegetation or animals that were negatively affected; possible human exposures; occupational status of the complainant at the time of the drift; results of laboratory testing of samples; and weather conditions at the time of application. Appendix B details each variable and its selection criteria.

Using case narratives, additional data were gathered using public databases. Weather (temperature, relative humidity, wind, and wind gusts) was obtained from historical public records (https://www.wunderground.com/) matching the date, time, and location of the reported drift event, using arithmetic average over the reported application period. A nearby town/city was utilized in cases where the specific required data was not available from the database. Distance data (from field to house and field to desirable vegetation) was estimated from Google Maps when not specified in the case report. When narratives contained no sampling maps, desirable vegetation nearest to the target field was randomly selected.

Drift Feedback Survey

In addition to using state drift reporting records, a convenience sample survey was conducted to examine the extent of pesticide drift underreporting. It included questions concerning any pesticide drift exposure to crops, animals, and humans during a pesticide drift event; whether the participant reported the incident; and if they knew how to report the incident in their state. Demographic data collected included age, gender, race, and state of residence. Open-ended questions asked whether drift had entered their property or work area, if anything was negatively affected by the drift, what specific chemicals were involved, how the pesticides were applied, a short description of what happened, did they report the drift and do they know how to report it, how would they prefer to report the incident, and recommendations for preventing drift in the future.

The survey was administered in person during the 2017 Farm Progress Show in Illinois. Online, people were invited through Facebook and email listserves to complete the survey, which was distributed to the following organizations: Farm Wives, Women in Agriculture, Iowa Farmer's Union, Missouri Farmer's Union, Agricultural Safety and Health Council of America, the National Agriculture Safety Database subscribers, Women, Food, and Agriculture Network, and the Great Plain's Center for Agricultural Health. Invitations to participate were also sent to email listserves, including: the Good Neighbor Iowa Program, Iowa Farm Bureau, Practical Farmers of Iowa, the Women, Food, and Agriculture Network, and the Iowa, Illinois, and Missouri Farmer's Unions. Surveys of the public were conducted between August 2017 and January 2018.

Data Analysis

Data analysis was performed with SAS software (Version 9.4). Descriptive statistics were used to characterize the drift events by state and through survey responses. Chi-square tests were performed to determine the dependency of the predictor variables (e.g., wind speed, wind gust, private/commercial applicator, land/aerial application, and target crop) on the outcome variables (damage to vegetation, livestock, bees, and people). Damage type was coded as damaged/exposed (1) or non-damaged/exposed (0). Dashes indicate no data was available for analysis. A t-test was conducted to determine whether the mean distance to the house or to the desired vegetation for each predictor variable were significantly different. Odds ratios with a 95% confidence interval (95% CI) were calculated to assess the relationship between the outcome and predictor variables. When the significance probability of the statistic was less than 0.05, the Satterthwaite probability was reported. When a cell contained an $N < 5$, the Fisher's exact test probability was reported instead of the chi-square probability result.

Results

State Regulations and Case Numbers

From the state-reported pesticide drift records, Iowa had 471 reported drift incidents over six years (72% confirmed instances of drift), Indiana had 391 reported incidents over six years (68% confirmed), and Michigan had 91 reported incidents over three years (64% confirmed). Michigan had substantially fewer cases per year (30 on average) compared to both Iowa (78) and Indiana (65). When assessing the case number using prevalence per 1 million acres of crop however, Indiana had the highest prevalence; 27 cases per 1 million acres of corn farmed, and 17 cases per 1 million acres of soybeans. When looking at prevalence by population (per 100,000 people), Iowa had the highest prevalence with 15 cases per 100,000 people. Figure 1 identifies reported cases by year and the crop for which the application was intended. The majority of incidents in Iowa involved corn as the target crop (52%), followed by soybeans (28%). In Indiana, the results were similar, with corn being the most targeted crop (39%), followed by soybeans (25%). In Michigan however, the majority (69%) of the pesticide drift cases were for applications to blueberry, orchard, and potato crops ("other"). Although not shown on the figure, pesticide container labeling was amended in 2010, to provide more information for applicators.

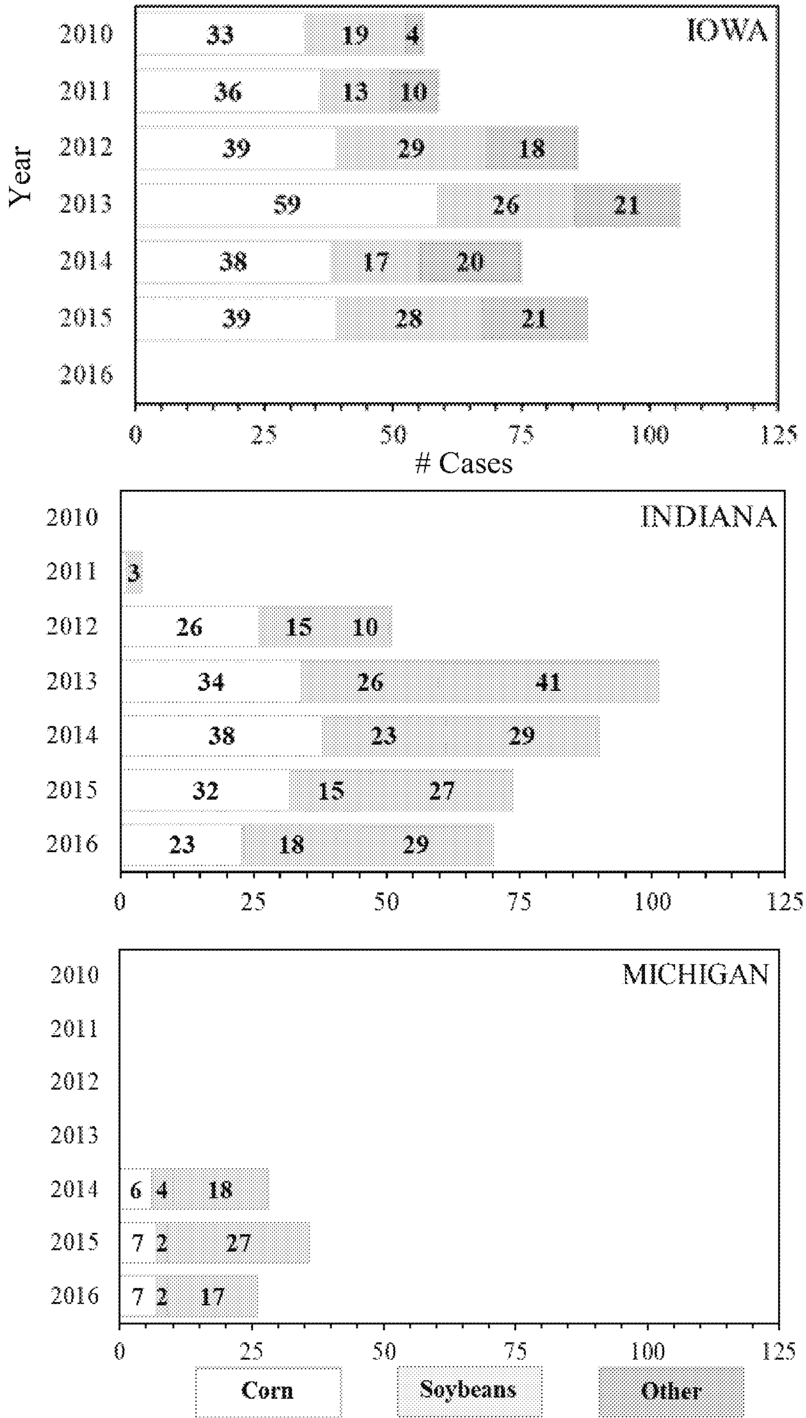

Figure 1. Number of drift incidents per year per state and the corresponding targeted crop for application.

Table 4. Comparisons of Iowa, Indiana, and Michigan state regulations concerning pesticides.

Variable	Iowa	Indiana	Michigan
Registration of pesticides	+	+	+
Licensing of applicators	+	+	+
Renewal of application licenses	+	+	+
Civil penalties	+	+	+
Exemptions from licensing	+	+	+
Language concerning drift of pesticides	+	+	+
Language concerning exposure to livestock	+	-	-
Language concerning exposure to bees	+	-	-
Notification of drift required	-	-	+

Iowa, Indiana, and Michigan require pesticides to be registered with state agriculture bureaus and they require that all pesticides have adequate labels (Table 4); the EPA also requires that pesticides be registered federally. Labels of commercially available pesticides list max wind speeds, with 4.5 m/s and 6.7 m/s being the most common label requirements. Otherwise, labels do not specify critical weather conditions for safe applications, instead stating that applicators should refrain from spraying in conditions that are too hot, too dry, or when inversions are present. However, the Ontario Ministry of Agriculture, Food, and Rural Affairs in Ontario, Canada recommends that spraying not occur in temperatures that are greater than 25°C and when humidity is less than 40%.[87]

Across the states studied here, the pesticides most commonly involved in pesticide drift events were: 2,4-dichlorophenoxyacetic acid (2,4-D), acetochlor, atrazine, glyphosate, pyraclostrobin, metolachlor, saflufenacil, prothioconazole, and tebuconazole. Of the above pesticides, 2,4-D, acetochlor, atrazine, glyphosate, metolachlor, and saflufenacil are herbicides; the others are fungicides.

Table 5 summarizes the conditions for 839 confirmed drift cases in which the applicator did not conform to application conditions for the nine pesticides listed above. Of these cases, 40% of applications occurred in wind speeds greater than 4.5 m/s, and 44% occurred when wind gusts were above 6.7 m/s. Since temperature and humidity are rarely given tangible limits on pesticide labels, it is not surprising that 33% of applications occurred when humidity was less than 40% and 21% occurred in conditions with a temperature greater than 25°C. When temperatures are greater than 25°C and/or humidity is less than 40%, the conditions are too hot and dry; this can allow for volitization of pesticides and drift to occur. The EPA requires a minimum 7.6 m buffer zone around the targeted crop when a soil fumigant is used; plus an 18 m buffer during land applications, and a 91 m buffer during aerial applications near habitats for Pacific salmon and steelhead.[88, 89] Although no soil fumigants or the associated pesticides were included in this data set, the 7.6 m buffer zone was used for analysis. Across all three states, 31% of drift cases involved buffers of less than 7.62 m between the targeted crop and affected desirable vegetation.

Table 5. Number of confirmed incidents in which label or government recommendations were violated when applying the most common pesticides.

Pesticide	N	Wind >4.5 m/s	Wind >6.7 m/s	Gusts >6.7 m/s	°C >25°	Humidity <40%	Distance <7.6 m
2,4-D	150	56	18	73	40	26	47
Acetochlor	63	26	12	20	23	12	22
Atrazine	139	62	19	64	51	31	46
Glyphosate	266	111	37	130	97	58	99
Pyraclostrobin	58	26	6	23	22	12	4
Metolachlor	70	26	12	34	19	18	25
Saflufenacil	58	24	6	23	11	15	16
Prothioconazole	24	6	1	2	10	1	2
Tebuconazole	11	2	0	1	3	0	1
Total	839	339 (40%)	111 (13%)	370 (44%)	276 (33%)	173 (21%)	262 (31%)

Drift Case Evaluation

Table 6 presents descriptive statistics for the continuous variables collected from case reports. The mean distance from the edge of the target field to either desirable vegetation (12 m) or the complainant's house (62 m) was largest in Iowa, compared to Indiana (10 and 53 m) and Michigan (7 and 35 m). Drift cases for applicators in Iowa occurred during higher wind conditions, with a mean wind speed of 4.1 m/s compared to Indiana (3.7 m/s) and Michigan (3.3 m/s). Iowa drift cases also occurred in hotter conditions, at 21.5$^{\circ C}$ compared to Indiana (20.9°C) and Michigan (20.7°C). Michigan applicators involved in reported drift events applied in the most humid weather, at 60.9%, compared to Iowa (57.8%) and Indiana (56.6%).

Table 6. Descriptive statistics for the distances from the edge of the field to the desired vegetation and the complainant's house, and the weather.

Variable	Units	N	Arithmetic Mean	Median	CI, 5-95%	Standard Deviation
			IA			
Distance from field to complainant house	m	429	61.6	50.9	12.4-584	3.52
Distance from field to desirable vegetation*	m	320	11.9	11.5	1.75-81.4	3.35
Wind speed	m/s	455	4.09	4.26	1.79-8.90	1.65
Wind gust*	m/s	242	9.30	9.11	5.81-15.2	1.31
Temperature	°C	454	21.5	23.1	11.7-30.6	1.36
Relative humidity†	%	454	57.8	59.0	29.0-85.5	17.0
			IN			
Distance from field to complainant's house	m	350	53.0	42.9	15.5-369	2.83
Distance from field to desirable vegetation	m	285	10.4	10.1	1.82-73.7	3.06
Wind speed	m/s	354	3.74	3.78	1.79-7.39	3.78
Wind gust	m/s	136	9.11	8.93	7.17-11.6	1.18
Temperature	°C	355	20.9	21.4	10.5-29.2	6.34
Relative humidity†	%	353	56.6	56.0	30.0-83.0	16.2
			MI			
Distance from field to complainant's house*	m	50	34.7	32.3	5.49-603	3.80
Distance from field to desirable vegetation*	m	35	7.08	6.02	0.00-661	6.16
Wind speed*	m/s	82	3.29	3.13	1.34-7.61	1.63
Wind gust†	m/s	25	9.49	9.39	4.92-13.8	2.59
Temperature	°C	79	20.7	21.7	9.44-28.0	5.49
Relative humidity†	%	79	60.9	62.0	30.0-91.5	18.3

*Data were lognormally distributed
†Data were normally distributed

Several characteristics have been found to be associated with drift distance (Table 7). In Iowa, the mean drift distance to the house was significantly larger when a private applicator conducted spraying compared to a commercial application, and Iowa had a significantly smaller mean drift distance to vegetation during aerial applications. In Indiana, there was a significantly larger mean drift distance to the house when corn was the target crop compared to other crops, and there was a significantly larger mean drift distance to vegetation during commercial applications compared to private ones. In Michigan, there was a significantly smaller mean drift distance to the house when an application occurred during high winds versus low, and a significantly larger mean drift distance to vegetation during aerial applications versus land.

Table 7. Associations via t-test between drift characteristics and drift distance.

Variable		Distance to complainant's dwelling			Distance to desirable vegetation		
		IA	IN	MI	IA	IN	MI
	Low vs. High Wind Speed	0.296*	0.353	**0.021***	0.336	0.713	0.235
	Low vs. High Wind Gusts	0.775	0.154	0.405	0.230	0.492	0.331
	Land vs. Aerial	0.517*	0.140	0.098	**0.020**	0.482*	**<0.001**
Applied by:	Commercial/Certified	0.057*	0.762	0.631	0.420	**0.043**	0.269*
	Private/Farmer	**0.006***	0.984	0.406	0.277	0.204	0.284
Target crop:	Corn	0.790	**0.028**	0.186	0.952	0.465	0.411
	Soybeans	0.907	0.789	-	0.891	0.874	-

* = Satterthwaite probability
Bold numbers indicate significant differences

Table 8 presents the associations between drift characteristics and damaged property—vegetation, animals, or humans, using chi-squared tests. In Iowa, vegetation damage was more frequent in high wind; animal damage was more frequent during aerial applications; and people were more frequently affected during aerial applications and when corn was the target crop. In Indiana, vegetation damage was more frequent when pesticides were applied aerially, when the applicator was commercial, and when soybeans were the target crop. Animal damage in Indiana was more frequent in high wind speeds, and people were affected more often during aerial applications, and during land conditions in high wind. In Michigan, vegetation damage was more frequent when corn was the target crop.

Table 8. Comparisons of differences in reported damages, by state with p-values of chi-square tests.

			Damage to:				
State	Comparisons	Sub Groups	Crops	Trees	Bees	Livestock	People
Iowa	Aerial vs Land	-	**0.014**	**<0.001**	**0.001**	**0.015**	**<0.001**
	Low vs High Wind	Land	0.389	0.875	0.305*	1.000*	0.075
		Aerial	0.759	0.358*	0.083	0.097	0.670
		Combined	0.449	0.679	0.436	0.329	0.577
	Low vs High Gusts	Land	0.778	**0.003**	0.072*	0.586	0.374
		Aerial	0.693	1.000*	0.236	0.109	0.187
		Combined	0.882	**0.009**	0.815	0.522	0.671
	Applied By	Commercial	0.643	0.423	0.908	0.533	0.700
		Farmer	0.747	0.380	1.000*	0.920	0.976
	Target Crop:	Corn	0.464	0.278	0.770	0.541	**0.024**
		Soybeans	0.971	0.302	0.492	0.386	0.351
Indiana	Aerial vs Land	-	**0.004**	**<0.001**	0.415*	1.000*	**<0.001**
	Low vs High Wind	Land	0.794	0.684	0.067*	0.374*	**0.005**
		Aerial	0.182*	1.000*	1.000*	1.000*	0.138*
		Combined	0.371	0.865	**0.044***	0.571*	0.457
	Low vs High Gusts	Land	0.642	0.945	0.223*	0.566*	0.070
		Aerial	0.495*	0.232*	1.000*	1.000*	0.098
		Combined	0.292	0.249	0.078	0.649	0.682
	Applied By	Commercial	0.100	**0.004**	0.220	0.484	0.452
		Farmer	0.456	**0.049**	0.725	0.376	0.223
	Target Crop	Corn	0.146	0.057	0.304	0.556	0.905
		Soybeans	0.385	**0.021**	0.097	0.865	0.160
Michigan	Aerial vs Land	-	0.152	1.000*	-	0.112*	0.151
	Low vs High Wind	Land	0.752*	0.392*	-	0.521*	0.792
		Aerial	1.000*	1.000*	-	1.000*	1.000*
		Combined	0.757*	0.426*	-	0.315*	0.585
	Low vs High Gusts	Land	0.470*	1.000*	-	1.000*	0.544*
		Aerial	-	-	-	-	-
		Combined	0.422*	1.000*	-	1.000*	0.565*
	Applied By	Commercial	0.080	0.742*	-	0.650*	0.219
		Farmer	0.123	0.709*	-	1.000*	0.433
	Target Crop	Corn	**0.015***	1.000*	-	1.000*	0.488
		Soybeans	-	-	-	-	-

Bold = significant p-value
*Fisher's test p-value

Odds ratios were used to characterize the risk of damage to vegetation, animals, and humans under various conditions. Table 9 contains the odds of damage under high wind conditions compared to low wind for all reported cases. An odds ratio less than 1.0 meant the drift characteristic was protective against damage and an odds ratio greater than 1.0 meant the drift characteristic was more likely to cause damage. The only significant odds ratio was identified in Indiana, where a human exposure was 2.6 times (95% CI: 1.3-5.2) more likely when pesticides were applied via land equipment. Since this is the only significant result out of 72 odds rations, it is possible that this significant value may be an artifact.

The associations between damage, application method, and target crop are provided in Table 10. In Iowa and Indiana, an aerial application was significantly associated with less vegetation damage (OR = 0.10). Overall, however, aerial pesticide applications were over 5 times more likely to affect both animals and humans. Overall, commercial applicators were less likely to cause vegetation damage (OR = 0.60) than private applicators. In Iowa, human exposure was 1.61 times more likely to occur in reported drift cases when corn was the target crop.

Table 9. Odds ratios (OR) of damage at low (referent) and high wind speeds by pesticide applications method.

Damage Type			Iowa OR (95% CI) N = 471	Indiana OR (95% CI) N = 391	Michigan OR (95% CI) N = 91	Overall OR (95% CI) N= 953
Vegetation	High	Land	1.52 (0.82-2.85)	1.14 (0.58-2.24)	0.74 (0.26-2.16)	1.20 (0.80-1.79)
	Wind*	Aerial	0.81 (0.40-1.66)	2.47 (0.49-12.6)	-	1.08 (0.59-1.97)
		Combined	0.99 (0.66-1.49)	1.71 (0.98-3.02)	0.82 (0.31-2.14)	1.15 (0.86-1.55)
	(Low					
Animal	Wind is	Land	1.62 (0.59-4.47)	0.68 (0.26-1.77)	0.38 (0.04-3.65)	0.88 (0.47-1.66)
	Referent	Aerial	1.02 (0.46-2.30)	0.27 (0.03-2.47)	-	0.72 (0.37-1.40)
	Group)	Combined	1.32 (0.74-2.46)	0.46 (0.20-1.08)	0.18 (0.02-1.53)	0.79 (0.51-1.24)
Human		Land	0.58 (0.32-1.06)	**2.60 (1.30-5.19)**	0.86 (0.29-2.53)	1.08 (0.72-1.62)
		Aerial	1.16 (0.58-2.32)	0.26 (0.05-1.45)	0.83 (0.05-15.1)	0.93 (0.52-1.64)
		Combined	0.89 (0.59-1.34)	1.24 (0.70-2.20)	0.76 (0.29-2.00)	1.00 (0.74-1.36)
Vegetation	High	Land	1.12 (0.61-2.06)	0.80 (0.42-1.52)	1.80 (0.14-23.4)	0.92 (0.54-1.24)
	Gusts*	Aerial	0.74 (0.36-1.53)	4.37 (0.74-25.8)	-	1.16 (0.62-2.18)
		Combined	0.89 (0.59-1.33)	1.61 (0.94-2.76)	1.67 (0.13-21.2)	0.97 (0.72-1.32)
	(Low					
Animal	Gust is	Land	2.64 (0.90-7.79)	0.87 (0.36-2.12)	-	1.32 (0.70-2.50)
	Referent	Aerial	1.07 (0.47-2.39)	0.41 (0.04-3.89)	-	0.80 (0.40-1.60)
	Group)	Combined	1.55 (0.85-2.86)	0.56 (0.26-1.22)	-	1.00 (0.64-1.57)
Human		Land	0.76 (0.43-1.37)	1.87 (0.94-3.71)	0.29 (0.02-3.83)	1.24 (0.81-1.89)
		Aerial	1.59 (0.79-3.20)	0.16 (0.02-1.47)	-	1.22 (0.67-2.21)
		Combined	1.09 (0.72-1.65)	0.89 (0.50-1.58)	0.35 (0.03-4.42)	1.15 (0.84-1.57)

Bolded data indicate significant odds ratios
*High wind ≥ 4.5 m/s; High gusts ≥ 6.7 m/s

Table 10. Odds ratios of damage for method of application and target crop.

Damage Type		Iowa OR (95% CI) N = 471	Indiana OR (95% CI) N = 391	Michigan OR (95% CI) N = 91	Overall OR (95% CI) N= 953
Vegetation	Land	Referent	Referent	Referent	Referent
	Aerial	**0.10 (0.06-0.16)**	**0.04 (0.02-0.09)**	0.38 (0.14-1.01)	**0.10 (0.07-0.14)**
	Farmer	Referent	Referent	Referent	Referent
	Commercial	1.10 (0.70-1.73)	**0.56 (0.34-0.91)**	0.43 (0.18-1.04)	**0.62 (0.43-0.90)**
	Other Crops	Referent	Referent	Referent	Referent
	Corn	0.99 (0.66-1.49)	1.11 (0.68-1.84)	2.84 (0.98-8.24)	1.20 (0.90-1.61)
	Soybeans	0.90 (0.58-1.40)	1.82 (0.97-3.40)	-	1.33 (0.94-1.88)
Animal	Land	Referent	Referent	Referent	Referent
	Aerial	**6.44 (3.38-12.3)**	**6.11 (2.92-12.8)**	**4.19 (1.24-14.1)**	**5.58 (3.61-8.62)**
	Farmer	Referent	Referent	Referent	Referent
	Commercial	1.03 (0.52-2.06)	1.18 (0.60-2.31)	2.08 (0.53-8.19)	1.55 (0.88-2.74)
	Other Crops	Referent	Referent	Referent	Referent
	Corn	0.66 (0.36-1.21)	1.00 (0.51-1.99)	1.08 (0.27-4.35)	0.79 (0.51-1.21)
	Soybeans	1.67 (0.89-3.11)	0.66 (0.28-1.55)	-	1.08 (0.67-1.75)
Human	Land	Referent	Referent	Referent	Referent
	Aerial	**5.69 (3.63-8.92)**	**8.59 (4.46-16.5)**	1.98 (0.77-5.10)	**5.92 (4.22-8.31)**
	Farmer	Referent	Referent	Referent	Referent
	Commercial	0.91 (0.57-1.45)	1.23 (0.71-2.12)	1.74 (0.72-4.24)	1.26 (0.87-1.83)
	Other Crops	Referent	Referent	Referent	Referent
	Corn	**1.61 (1.06-2.44)**	0.97 (0.55-1.69)	0.69 (0.25-1.95)	1.20 (0.89-1.62)
	Soybeans	0.80 (0.50-1.28)	0.61 (0.30-1.22)	-	0.66 (0.46-0.96)

Bolded data indicate significant odds ratios.

Survey Results

The farmer surveys resulted in 142 respondents, with 56 from Iowa, 0 from Indiana, and 2 from Michigan. On average, the respondents were 51 years old, and 53% were male. Seventy-four percent reported drift into their property or work area. Of the 85 who reported damage to property, 39% reported crop damage, 17% reported damage to animals, and 34% reported that people were affected. Only 30% of respondents (27% IA) reported the drift incident to appropriate authorities; the majority of respondents (54% IA) had no idea how to report the drift incident in their state. Since only 40% of respondents knew how to report drift incidences, it is likely that the state case records used in this analysis may not accurately reflect pesticide drift characteristics.

During applications in which drift was reported to have occurred, 33% of those surveyed reported windy conditions, 17% reported a strong taste or smell in the air, 13% reported the aerial applicators did not turn off the spray over their property, and 24% reported workers being exposed. Farm hands and property owners reported being directly sprayed, while some survey respondents mentioned that workers were in the fields/surrounding areas during spraying. Survey participants were asked to provide recommendations to reduce drift incidents in the future: these included larger penalties and stronger regulations (36%), more interaction and warning between neighbors (25%), better education and training (22%), an emphasis on understanding land use around a targeted site (20%), and more easily available weather information (7%).

Discussion

Overall, Iowa (78/yr) and Indiana (65/yr) reported more drift cases than Michigan (30/yr). If the overlapping years of 2014-2015 are studied, Iowa and Indiana had comparable case averages at 81 and 82 cases per year on average respectively. Michigan still had the smallest average at 32 cases per year on average. Indiana had the most cases per acre however (27 per 1 million acres of corn and 17 cases per 1 million acres of soybeans) and Iowa had the most cases per 100,000 people (15 per 100,000 people). The major cash crop in all three states was corn, however the majority of reported drift incidents in Michigan involved blueberries and potatoes. Different crops require different pesticides and pesticide application methods, which indicates crop-specific pesticide drift prevention plans are needed.

However, there was sufficient data to provide generalizable recommendations for row crops. The mean distance drift traveled from targeted crops to desirable vegetation, across all three states, was about 10 m, with 31% of cases having an application distance less than the EPA recommended 7.62 m. Increasing the buffer zone between targeted crops and surrounding vegetation would decrease the likelihood of drift endangering neighboring properties. The mean wind speed during application times was about 4 m/s, just under a max label recommendation of 4.5 m/s; 41% of cases had applications occur during wind speeds greater than 4.5 m/s. A better understanding of acceptable application conditions could reduce applications above recommended guidelines, possibly reducing drift events.

Several drift characteristics have been associated with increasing or decreasing drift distance during applications. Theoretically, higher wind speeds should cause pesticides to drift further, but in Michigan, a higher wind speed was associated with a shorter drift distance to nearby homes. In Iowa and Michigan, the effect of aerial applications on drift distance was conflicting. In Iowa, drift distance was shorter during aerial applications, but in Michigan the distance was larger. There was also conflicting data on which type of applicator (i.e., private or commercial) affected drift distance. In Iowa, a private applicator was associated with larger drift distances, but in Indiana, larger drift distances were associated with commercial applicators. Due to the conflicting results, it is impossible to make overarching recommendations for all states. Instead, individual state recommendations are required to address the state specific drift characteristics causing increased drift distances.

Several drift characteristics were found to be associated with more damage to surrounding property and people. In Iowa and Indiana, drift cases that damaged surrounding property and affected people were more common during aerial applications. In Iowa, more damage to trees occurred during land equipment pesticide applications in windy conditions. In Indiana however, damage to trees was more associated with commercial applicators, compared to private ones. In Michigan, damage to crops from pesticide drift was more common when the target crop was corn. If applications occur in low wind conditions, land equipment should be used, as land equipment was not associated with any type of damage in low wind conditions compared to aerial equipment. Since commercial applicators were more associated with damage, improved training and educational materials should be developed in an effort to reduce drift cases.

The risk of damage from drift varied between states. Human exposure from pesticide drift was 2.6 times more likely when a land application was conducted in high wind compared to low wind conditions; this observation was only present in Indiana. Considering only 91 cases were recorded in Michigan, it is unknown whether this trend would have been present in this state as well. Overall, aerial and commercial applications had lower odds of vegetation damage, however most aerial applications contain insecticides, which does not cause plant damage. Aerial applications were, however, significantly associated with both animal and human exposures in reported cases. This might be due to the high visibility of aerial applications versus land based ones, prompting more proactive reporting. Iowa was the only state in which human exposure was more likely (1.61 times) when corn was the target crop compared to other crops; which differed in other states. This is an interesting finding considering Indiana had more cases per 1 million acres of corn. Further investigation is needed to determine if other factors are affecting applications to corn crops.

Differences between state regulations may contribute to the number of drift incidents each year. All three states require pesticides be registered, applicators be licensed, and the renewal of application licenses (different depending on the state and the equipment used). They all also identify potential civil penalties, provide licensing exemptions for some applicators, and define pesticide drift. Applicators exempt from licensure in Iowa include farmers whom use pesticides for their own use on their farm, farmers whom operate the equipment on their, or their neighbor's property, and persons whom use hand-powered or self-propelled equipment with less than 7.5 horsepower for use on their own property with non-restricted pesticides.[90] Exemptions in Indiana include farmers whom apply pesticides for their own use on their or their neighbor's property, farmers whom do not use restricted pesticides, veterinarians whom use pesticides as a part of their practice, and research personnel applying in experimental plots.[91] In Michigan, exemptions include employees applying under supervision of certified personnel, people applying general use pesticides for private purposes, allopathic and osteopathic physicians veterinarians, and researchers.[92]

However, only Iowa's regulations addresses exposure to bees and livestock, and only Michigan requires notifying neighbors when drift occurs. Michigan also offers resources for the development of drift management plans for commercial businesses and farmers. Michigan's resources, which includes a template drift management plan, might be associated with the reduced number of drift incidences because it includes procedures for pesticide application and specifies conditions that increase the risk of pesticide drift. However, more data are needed to determine whether this plan reduces the amount of drift occurrences. Being held responsible for reporting drift to neighbors might also reduce drift occurrences or reporting of events to the state. Regardless of the legal code, our survey of the public indicated that 60% of them do not know how to report a drift if it occurs. This may contribute to underreporting of pesticide drift in state records. However, our survey was only sent out to agriculture related groups, not the entire community, which means the survey responses are biased and not a true representation of community drift exposure in general.

A lack of awareness, or adherence, to application recommendations during risky weather conditions is reflected in both case records and the farmer survey. Fifty-three percent of applications in which drift was confirmed occurred when normal wind speeds exceeded the 6.7 m/s recommendation, and 44% of applications occurred in conditions with wind gusts greater than 6.7 m/s. Sixteen percent of applications violated both buffer zone requirements and wind speed recommendations. Accounting for confirmed drift cases means that in high wind conditions, when a subpar buffer zone was utilized, pesticide drift occurred 4.4% of the time. However, since the wind speed data was averaged over long time, any results may be biased towards the null, that is that there is no difference between states or conditions; thus weakening any associations. With a large portion of applications taking place under unacceptable conditions, better communication and education about the importance wind speed and buffer zones would reduce the impact of pesticide drift.

Based on this information there are several key factors that should be included when pesticide drift reports are investigated. While investigations always included wind speeds and gusts, they did not include temperature or humidity data. And while temperature and humidity were not associated with more damage or drift distance, since there are recommended limits they should be recorded. Distance was also rarely recorded outside of stating sampling locations. With a minimum buffer zone provided by the EPA, distance from the field to the edge of property should be recorded to determine if this rule has been violated. Since there are exemptions for pesticide applicator licensure, the private applicator's status should be recorded. Licensure means more education and training, which could reduce the incidences of drift. By recording the above key factors, a better understanding of drift characteristics will develop. Recording this information could also shape label recommendations; as it stands right now, many labels simply say not to apply in certain conditions, but do not provide applicators with specific numbers.

Limitations

There are several limitations associated with this study. Both Iowa and Michigan records were narrative in form, prepared by multiple investigators, and not always complete, with several factor unavailable for each case. Sometimes weather data was not available for the location of a case, which required using the next closest city and weather information. Local microclimates were not included in the wind analysis. Weather data was also averaged over the reported application period, which ranged anywhere from 5 minutes to 12 hours, which might reduce peak wind speed associated with the specific drift event. In addition, case reports rarely included distance information, specifically from the field where pesticides were being applied to the reported damaged property or homestead. Distance estimates, for this study, relied on rough drawn sketches, if available, or picking the closest tree or bush on the property to the targeted field using Google Maps. Data coding for vegetation affected prioritized crop damage over ornamental plants or tree damage. The survey was a convenience sample of agriculturally minded people, which may have resulted in biased responses. A more widely distributed survey, to include non-agricultural participants, may have given a better indication of the true prevalence of pesticide drift. Finally, although the findings of this research are important moving forward, reported drift cases do not represent all drift cases in general. People might report drift only after seeing damage or the application equipment. Random observations of pesticide applications would need to be conducted to determine if reported drift cases are representative of all drift cases.

Recommendations

Additional education is needed to communicate how to prevent and report pesticide drift. State reporting systems vary, but rural residents and farmers need clear information on state reporting procedures. Possible mechanisms include dissemination through local cooperatives and extension agents for farmers, and possible rural utility providers for other rural residents potentially affected by pesticide drift. Finally, requiring formal drift management plans may also reduce drift occurrences, with clearly defined application limitations reviewed prior to heavy pesticide use seasons. While state pesticide agencies can fine applicators (in these three states between $250 and $500 per offence) who drifted while not following rules, with these funds use to train and educate applicators (IN) to decrease incidences of drift or to conducting future drift investigations (MI). In Indiana, all money received from pesticide violation citations is immediately funneled into extension programs aimed at educating and training commercial applicators; in Michigan the penalties are used to fund future investigations.

Future databases and investigations should collect data relating to relative humidity, temperature, buffer zones, and more in-depth information about private applicators. Collecting this type of data will allow for comparisons to established recommendations. Recording the specific type of private applicator will allow for comparison to specific state exemptions. Since state and federal regulatory agencies have provided weather and distance limits, recording this information can allow for regulatory enforcement. Future databases should allow for a complainant's detailed comments. While the information an investigator includes is important, narratives can also be enlightening when studied. If feasible, a state should establish which crops are the most common and then determine if one crop leads to more pesticide drift cases; this will allow for more focused enforcement and training.

Conclusion

Cases of pesticide drift that were reported to agencies in three Midwestern states occurred more frequently when applied during high wind speed (> 4.5 m/s), when applied via aerial equipment, and when applied to corn. Between-state drift differences were identified, which may be affected by differences in regulations and training requirements. While Michigan regulations requires applicators to notify neighbors when pesticide drift occurs, Michigan's production differences may also contribute to fewer reports of pesticide drift cases. Sixty percent of people surveyed indicated they did not know how to report an incident if it did occur, the state reporting records of pesticide drift may be biased, with an underestimation of case incidence likely.

CHAPTER 3: CONCLUSIONS

The review of pesticide drift records across three Midwestern states identified several important outcomes. The most common pesticides involved in drift events included 2,4-D, acetochlor, atrazine, glyphosate, pyraclostrobin, metolachlor, saflufenacil, prothioconazole, and tebuconazole. Iowa had the most cases occur per year on average, and Michigan had the least; Indiana had the highest prevalence rates however. The type of application (aerial/land), the type of applicator (commercial/private), high wind gusts, and target crop all affected the distance pesticides traveled and the type of damage incurred. A large proportion of cases also involved applications occurring contrary to label recommendations. A distressingly small percentage, 40%, of surveyed individuals knew how to report incidences of drift. Overall, this means that several interventions can be implemented to reduce incidences in the future. Spray equipment can be modified to reduce the potential for drift, both commercial and private applicators could have access to better weather information and educational material, and information about reporting incidences can be disseminated tot rural locations. Based on the outcomes of this research, several interventions are available.

However, this data set did not contain 2017 data. This is important because dicamba became popular in 2017, and as a result, the number of reported drift cases was almost 3 times greater than usual due to the dicamba volatilizing and/or drifting. Dicamba, an herbicide registered in the late 60's with the EPA, has become a hot button topic in agriculture. Because it can only be applied to crops that are genetically engineered to be resistant to dicamba, and because it has become wildly popular, it has led to a rash of pesticide drift complaints. In Iowa alone, 2017 saw over 200 reported cases of pesticide drift, much higher than the average 78 cases seen per year. Although our research was conducted 2017 to 2018, the use of data from previous years meant we did not see an unusual amount of dicamba exposures. Therefore, the results of this data should be taken with a grain of salt, as there is still a lot to learn about pesticide drift, especially as it pertains to dicamba.

Drift reduction technology was not taken into account when addressing pesticide drift in this thesis. Largely because information on the exact equipment used to apply the pesticides was not available. The EPA has a drift reduction technology program, which aims to reduce drift by modifying spray nozzles, spray shields, and chemical formulas. In the future, research should be done to determine if there are any associations between reported drift cases and the use of drift reduction technology. If it can be proven that availability or affordability of the products is a barrier to applicators, thus increasing drift cases because the correct equipment is out of reach, programs and education can be made available.

The EPA has created, and made available, a worker protection standard (WPS) for pesticide application. In 2015, the old WPS was revised to provide stronger protections for workers and community members. By the end of 2018, several aspects of the new WPS will be introduced for public comment; this includes new requirements on minimum ages, representatives, and exclusion zones. In January of 2018, three new requirements came into effect: expanded pesticide safety training, revised safety posters, and the suspension of applications within the exclusion zone when workers or community members are within the exclusion zone. Many of the topics discussed in Chapter 2, coincidentally, are also covered within the WPS. The WPS requires pesticide safety training, access to specific information such as labeling, notification of applications to avoid accidentally contacting treated land, and keeping workers out of areas that are being treated.

Several career-long skills were learned during the course of this research. One of the most important lessons learned concerned ethics. During the course of this research, I dealt with many documents that contained names, phone numbers, and addresses of complainants and applicators. Maintaining confidentiality was crucial due to the recent fervor over pesticide drift; news agencies and anti-pesticide groups might use that information and twist it to bolster their own content. Potential retaliation among neighbors is also a possibility; some of the relationships expressed in case narratives were truly volatile.

The application of regulations, consensus standards, and best practices was another important aspect of this work. Only two of the nine chemicals had any type of occupational regulation, and a third had drinking water concentration limits. Many of the discussed weather conditions are simply best practices and are not regulated. The practice of taking these regulations and best practices and applying them to the data collected is an important skill to have.

Over the course of this research, and for several months after its completion, I have had to explain my research to various audiences and attempt to engage them in my research. This research has been presented at three different conferences as of March 2018, and as of June 2018, it will have been presented at two additional conferences and a pesticide networking meeting between various universities and researchers.

During the course of this research, ways to eliminate exposure to pesticides was extremely important. The easiest way to reduce pesticide drift is to institute administrative controls. In this case, more education about acceptable application conditions and better resources for surrounding land use, would go a long way to reduce drift. Some engineering controls would include buying more drift conscious equipment and less toxic pesticides. This research required analyzing the data and then taking the characteristics most likely to cause drift and determining whether a control could be implemented.

REFERENCES

1. Merriam-Webster, *Agriculture*. 2017.
2. Society, National Geographic. *Agriculture*. 2017; Available from: https://www.nationalgeographic.org/encyclopedia/agriculture/.
3. *Nobel Lectures, Peace 1951-1970*, ed. F.W. Haberman. 1972, Amsterdam: Elsevier Publishing Company.
4. Agency, Environmental Protection. *What is a pesticide?* 2017; Available from: https://www.epa.gov/minimum-risk-pesticides/what-pesticide.
5. Taylor, E, A. G Holley, and M Kirk, *Pesticide development: A brief look at the history*. Southern Regional Extension Forestry, 2007.
6. Agriculture, United States Department of, *Table 8. Land: 2012 and 2007 - Iowa*. 2012.
7. Agriculture, United States Department of, *Table 8. Land: 2012 and 2007 - Indiana*. 2012.
8. Agriculture, United States Department of, *Table 8. Land: 2012 and 2007 - Michigan*. 2012.
9. Agriculture, United States Department of, *Table 37. Specified Crops by Acres Harvested: 2012 and 2007 - Iowa*. 2012.
10. Agriculture, United States Department of, *Table 37. Specified Crops by Acres Harvested: 2012 and 2007 - Indiana*. 2012.
11. Agriculture, United States Department of, *Table 37. Specified Crops by Acres Harvested: 2012 and 2007 - Michigan*. 2012.
12. Service, National Agricultural Statistics, *Pounds of pesticide applied to soybeans*. 2015.
13. Service, National Agricultural Statistics, *Pounds of pesticides applied to corn*. 2016, United States Department of Agriculture.
14. Registry, Agency for Toxic Substances & Disease, *Toxicological Profile for 2,4-Dichlorophenoxyacetic Acid (2,4-D)*. 2015.
15. Services, Delaware Health and Social, *Acetochlor*. 2013.
16. Registry, Agency for Toxic Substances & Disease, *Toxicological Profile for Atrazine*. 2015, Agency for Toxic Substances & Disease Registry.
17. Henderson, A. M., J. A. Gervais, B. Luukinen, K. Buhl, and D. Stone. *Glyphosate General Fact Sheet*. 2010; Available from: http://npic.orst.edu/factsheets/glyphogen.html.
18. Products, BASF Agricultural, *Product Label for Headline Fungicide (EPA Reg. No. 7969-186)*. 2006. p. 32.
19. Agency, Environmental Protection, *Metolachlor health advisory*. 1987.
20. Agency, Environmental Protection, *Pesticide fact sheet: Saflufenacil*, P. Office of Prevention, and Toxic Substances Editor. 2009.
21. Agency, Environmental Protection, *Prothioconazole: Human Health Risk Assessment for Proposed Uses on Barley, Canola, Chickpea, Dried Shelled Peas and Beans (except Soybean), Lentils, Oilseed Crops (except Sunflower and Safflower), Peanut, Wheat, and Rice*, P. Office of Prevention, and Toxic Substances, Editor. 2007.

22. Database, Pesticide Properties. *Tebuconazole*. 2017; Available from: https://sitem.herts.ac.uk/aeru/ppdb/en/Reports/610.htm.
23. Jervais, G, B. Luukinen, K. Buhl, and D. Stone. *2,4-D General Fact Sheet*. 2008; Available from: http://npic.orst.edu/factsheets/24Dgen.html.
24. Network, Extension Toxicology. *Acetochlor*. 1996; Available from: http://pmep.cce.cornell.edu/.
25. *Herbicide Handbook of the Weed Science Society of America*. 6 ed. 1989, Champaign, IL.
26. Agency, Environmental Protection, *Acetochlor; Pesticide Tolerances*, E.P. Agency, Editor. 2014, Federal Register. p. 3512-3518.
27. Authority, European Food Safety, *Conclusion on the peer review of the pesticide risk assessment of the active substance acetochlor.* EFSA Journal, 2011. **9**(5).
28. *Farm Chemicals Handbook*. 1995, Willoughby, OH: Meister Publishing Co.
29. Committee, Federal-State Toxicology and Risk Analysis, *Summary of State and Federal Drinking Water Standards and Guidelines (11/93) to Present*. 1993, Environmental Protection Agency Office of Water.
30. Agency, Environmental Protection, *Report of the Food Quality Protection Act (FQPA) Tolerance Reassessment Progress and Risk Management Decision (TRED) for Acetochlor* 2006.
31. Agency, Environmental Protection, *Chemicals Evaluated for Carcinogenic Potential*. 2016, Environmental Protection Agency Office of Pesticide Programs.
32. *Modern Crop Protection Compounds*. Vol. 1. 2007: Wiley-VCH.
33. Network, Extension Toxicology. *Atrazine*. 1993; Available from: http://pmep.cce.cornell.edu/profiles/extoxnet/24d-captan/atrazine-ext.html.
34. Network, Extension Toxicology. *Glyphosate*. 1994; Available from: http://pmep.cce.cornell.edu/profiles/extoxnet/dienochlor-glyphosate/glyphosate-ext.html.
35. Service, Forest, *Pesticide Background Statements, Vol. I Herbicides*. 1984: United States Department of Agriculture.
36. Kreiger, R., *Handbook of Pesticide Toxicology*. 2 ed. Vol. 2. 2001: Academic Press.
37. Organization, World Health, *IARC Monographs Volume 112: evaluation of five organophosphate insecticides and herbicides*. 2015.
38. *The Agrochemicals Handbook*. 1991, Cambridge, England: The Royal Society of Chemistry.
39. Conservation, New York State Department of Environmental, *Pyraclostrobin - NYS Registrations: Insignia, Headline, and Cabrio 12/04*, N.Y.S.E. Conservation, Editor. 2004.
40. Agency, Environmental Protection, *Reregistration eligibility decision metolachlor: List A case 0001*, S.R.a.R. Division, Editor. 1995.
41. Network, Extension Toxicology. *Metolachlor*. 1993; Available from: http://pmep.cce.cornell.edu/profiles/extoxnet/metiram-propoxur/metolachlor-ext.html.
42. Agency, Environmental Protection, *Pesticide Regulation Standard for Metolachlor*. 1980.

43. Zimdahl, R.L. and S.K. Clarke, *Degradation of three acetanilide herbicides in soil.* Weed Science, 1982(30): p. 545-548.
44. Holden, L.R. and J.A. Grahm, *Results of the National Alachlor Well Water Survey.* Environmental Science and Technology, 1992. **26**: p. 935-943.
45. America, Weed Science Society of, *Herbicide Handbook.* 7 ed. 1994, Champaign, IL.
46. Agency, Environmental Health, *Pesticide Fact Sheet Number 106: Metolachlor.* 1987: Washington, DC. p. 10-101.
47. Bowe, S.J., K.E. Keller, C. D. Kleppe, and S. Tan, *Saflufenacil: Application to extend exclusive use period.* 2014.
48. Chemistry, International Union of Pure and Applied. *Prothioconazole.* 2017; Available from: https://sitem.herts.ac.uk/aeru/iupac/Reports/559.htm.
49. Meylan, W.M. and P.H.C Howard, *Computer estimation of the Atmospheric gas-phase reaction rate of organic compounds with hydroxyl radicals and ozone.* Chemosphere, 1993. **26**(12): p. 2293-2299.
50. Agency, Environmental Protection, *Pesticide Fact Sheet for Prothioconazole*, P. Office of Prevention, and Toxic Substances, Editor. 2007. p. 6, 17.
51. Regulations, Code of Federal, *Protection of Environment: Tolerances for residues.* 2007.
52. Agency, Environmental Protection, *Ecological Risk Assessment for Section 3 Registration of Tebuconazole on Wheat, Cucurbits, Bananas, Turnips, Tree nuts, Hops, and Sunflowers*, P. Office of Prevention, and Toxic Substances, Editor. 2000.
53. Agency, California Envrionmental Protection, *Toxicology Data Review Summary on Tebuconazole*, D.o.P. Regulation, Editor. 2006.
54. Safety, International Programme on Chemical. *Joint Meeting on Pesticide Residues on Tebuconazole (107534-96-3).* 1994; Available from: http://www.inchem.org/documents/jmpr/jmpmono/v94pr10.htm.
55. Bureau, U.S. Census. *Quick Facts: Michigan.* 2017; Available from: https://www.census.gov/quickfacts/MI.
56. Bureau, U.S. Census. *Quick Facts: Indiana.* 2017; Available from: https://www.census.gov/quickfacts/IN.
57. Bureau, U.S. Census. *Quick Facts: Iowa.* 2017; Available from: https://www.census.gov/quickfacts/IA.
58. Di, H. J., L. A. G. Aylmore, and R. S. Kookana, *Degradation rates of eight pesticides in surface and subsurface soils under laboratory and field conditions.* Soil Science, 1998. **163**(5): p. 404-411.
59. de Snoo, G. R. and R. J. van der Poll, *Effect of herbicide drift on adjacent boundary vegetation.* Agriculture Ecosystems & Environment, 1999. **73**(1): p. 1-6.
60. De Schampheleire, M., P. Spanoghe, E. Brusselman, and S. Sonck, *Risk assessment of pesticide spray drift damage in Belgium.* Crop Protection, 2007. **26**(4): p. 602-611.
61. Yarpuz-Bozdogan, N., *Assessment of buffer zone for aquatic organisms in pesticide application.* International Journal of Agricultural and Biological Engineering, 2016. **9**(5): p. 227-234.

62. de Snoo, G. R. and P. J. de Wit, *Buffer zones for reducing pesticide drift to ditches and risks to aquatic organisms.* Ecotoxicology and Environmental Safety, 1998. **41**(1): p. 112-118.
63. Alavanja, M. C. R., D. P. Sandler, C. J. McDonnell, C. F. Lynch, M. Pennybacker, S. H. Zahm, J. Lubin, D. Mage, W. C. Steen, W. Wintersteen, and A. Blair, *Factors associated with self-reported, pesticide-related visits to health care providers in the Agricultural Health Study.* Environmental Health Perspectives, 1998. **106**(7): p. 415-420.
64. Calvert, G. M., D. K. Plate, R. Das, R. Rosales, O. Shafey, C. Thomsen, D. Male, J. Beckman, E. Arvizu, and M. Lackovic, *Acute occupational pesticide-related illness in the US, 1998-1999: Surveillance findings from the SENSOR-pesticides program.* American Journal of Industrial Medicine, 2004. **45**(1): p. 14-23.
65. Slager, R. E., J. A. Poole, T. D. LeVan, D. P. Sandler, M. C. R. Alavanja, and J. A. Hoppin, *Rhinitis associated with pesticide exposure among commercial pesticide applicators in the Agricultural Health Study.* Occupational and Environmental Medicine, 2009. **66**(11): p. 718-724.
66. Payan-Renteria, R., G. Garibay-Chavez, R. Rangel-Ascencio, V. Preciado-Martinez, L. Munoz-Islas, C. Beltran-Miranda, S. Mena-Munguia, L. Jave-Suarez, A. Feria-Velasco, and R. De Celis, *Effect of Chronic Pesticide Exposure in Farm Workers of a Mexico Community.* Archives of Environmental & Occupational Health, 2012. **67**(1): p. 22-30.
67. Hoppin, J. A., D. M. Umbach, S. Long, S. J. London, P. K. Henneberger, A. Blair, M. Alavanja, L. E. B. Freeman, and D. P. Sandler, *Pesticides are Associated with Allergic and Non-Allergic Wheeze among Male Farmers.* Environmental Health Perspectives, 2017. **125**(4): p. 535-543.
68. Cremonese, C., C. Piccoli, F. Pasqualotto, R. Clapauch, R. J. Koifman, S. Koifman, and C. Freire, *Occupational exposure to pesticides, reproductive hormone levels and sperm quality in young Brazilian men.* Reproductive Toxicology, 2017. **67**: p. 174-185.
69. Andreotti, G., J. A. Hoppin, L. F. Hou, S. Koutros, S. M. Gadalla, S. A. Savage, J. Lubin, A. Blair, M. Hoxha, A. Baccarelli, D. Sandler, M. Alavanja, and L. E. B. Freeman, *Pesticide Use and Relative Leukocyte Telomere Length in the Agricultural Health Study.* Plos One, 2015. **10**(7).
70. Martinez-Valenzuela, C., S. Waliszewski, O. Amador-Munoz, E. Meza, M. E. Calderon-Segura, E. Zenteno, J. Huichapan-Martinez, M. Caba, R. Felix-Gastelum, and R. Longoria-Espinoza, *Aerial pesticide application causes DNA damage in pilots from Sinaloa, Mexico.* Environmental Science and Pollution Research, 2017. **24**(3): p. 2412-2420.
71. Lerro, C. C., S. Koutros, G. Andreotti, C. J. Hines, A. Blair, J. Lubin, X. M. Ma, Y. W. Zhang, and L. E. Beane Freeman, *Use of acetochlor and cancer incidence in the Agricultural Health Study.* International Journal of Cancer, 2015. **137**(5): p. 1167-1175.
72. Miligi, L., A. S. Costantini, A. Veraldi, A. Benvenuti, and P. Vineis, *Cancer and pesticides: An overview and some results of the Italian Multicenter case-control study on hematolymphopoietic malignancies.* Living in a Chemical World: Framing the Future in Light of the Past, 2006. **1076**: p. 366-377.

73. Agency, Environmental Protection. *Introduction to Pesticide Drift*. 2017; Available from: https://www.epa.gov/reducing-pesticide-drift/introduction-pesticide-drift.
74. Agency, Environmental Protection. *About the Drift Reduction Technology Program*. 2018; Available from: https://www.epa.gov/reducing-pesticide-drift/about-drift-reduction-technology-program.
75. Agency, Environmental Protection. *EPA-Verified and Rated Drift Reduction Technologies: Review of Test Reports and Assigning DRT Ratings to Technologies*. 2017; Available from: https://www.epa.gov/reducing-pesticide-drift/epa-verified-and-rated-drift-reduction-technologies.
76. Estellano, V. H., K. Pozo, C. Efstathiou, K. Pozo, S. Corsolini, and S. Focardi, *Assessing levels and seasonal variations of current-use pesticides (CUPs) in the Tuscan atmosphere, Italy, using polyurethane foam disks (PUF) passive air samplers.* Environmental Pollution, 2015. **205**: p. 52-59.
77. Carratala, A., R. Moreno-Gonzalez, and V. M. Leon, *Occurrence and seasonal distribution of polycyclic aromatic hydrocarbons and legacy and current-use pesticides in air from a Mediterranean coastal lagoon (Mar Menor, SE Spain).* Chemosphere, 2017. **167**: p. 382-395.
78. Solomon, K. R., D. Houghton, and S. A. Harris, *Nonagricultural and residential exposures to pesticides.* Scandinavian Journal of Work Environment & Health, 2005. **31**: p. 74-81.
79. Ward, M. H., J. Lubin, J. Giglierano, J. S. Colt, C. Wolter, N. Bekiroglu, D. Camann, P. Hartge, and J. R. Nuckols, *Proximity to crops and residential exposure to agricultural herbicides in Iowa.* Environmental Health Perspectives, 2006. **114**(6): p. 893-897.
80. Deziel, N. C., M. C. Friesen, J. A. Hoppin, C. J. Hines, K. Thomas, and L. E. B. Freeman, *A Review of Nonoccupational Pathways for Pesticide Exposure in Women Living in Agricultural Areas.* Environmental Health Perspectives, 2015. **123**(6): p. 515-524.
81. Lee, S. J., L. Mehler, J. Beckman, B. Diebolt-Brown, J. Prado, M. Lackovic, J. Waltz, P. Mulay, A. Schwartz, Y. Mitchell, S. Moraga-McHaley, R. Gergely, and G. M. Calvert, *Acute Pesticide Illnesses Associated with Off-Target Pesticide Drift from Agricultural Applications: 11 States, 1998-2006.* Environmental Health Perspectives, 2011. **119**(8): p. 1162-1169.
82. Thistle, H. W., J. A. S. Bonds, G. J. Kees, and B. K. Fritz, *Evaluation of Spray Drift from Backpack and Utv Spraying.* Transactions of the Asabe, 2017. **60**(1): p. 41-50.
83. Jomichen, J., S. El-Zaemey, J. S. Heyworth, R. N. Carey, E. Darcey, A. Reid, D. C. Glass, T. Driscoll, S. Peters, M. Abramson, and L. Fritschi, *Australian work exposures studies: occupational exposure to pesticides.* Occupational and Environmental Medicine, 2017. **74**(1): p. 46-51.
84. Harris, S. A., P. J. Villeneuve, C. D. Crawley, J. E. Mays, R. A. Yeary, K. A. Hurto, and J. D. Meeker, *National Study of Exposure to Pesticides among Professional Applicators: An Investigation Based on Urinary Biomarkers.* Journal of Agricultural and Food Chemistry, 2010. **58**(18): p. 10253-10261.

85. Thomas, K. W., M. Dosemeci, J. A. Hoppin, L. S. Sheldon, C. W. Croghan, S. M. Gordon, M. L. Jones, S. J. Reynolds, J. H. Raymer, G. G. Akland, C. F. Lynch, C. E. Knott, D. P. Sandler, A. E. Blair, and M. C. Alavanja, *Urinary biomarker, dermal, and air measurement results for 2,4-D and chlorpyrifos farm applicators in the Agricultural Health Study.* Journal of Exposure Science and Environmental Epidemiology, 2010. **20**(2): p. 119-134.
86. Agency, Environmental Protection. *Human Health Issues Related to Pesticides*. 2017; Available from: https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/human-health-issues-related-pesticides.
87. Ontario Ministry of Agriculture, Food, and Rural Affair. *Pesticide drift from ground applications*. 2011; Available from: http://www.omafra.gov.on.ca/english/crops/facts/11-001.htm.
88. Agency, Environmental Protection, *Calculating buffer zones: a guide for applicators.* 2016.
89. Agriculture, Washington State Department of. *Pesticide No-Spray Buffers Imposed by U.S. District Court Order*. 2017.
90. Code, Iowa, *Chapter 206.18 - Pesticides*. 2014.
91. Chemist, Iowa State, *IC 15-16-5-55*. 2008.
92. Development, Michigan Department of Agriculture and Rural, *Pesticide Control - 324.8319.* 1994.

APPENDIX A: CODED DATA ABBREVIATIONS

		IA Codes	
Variable	Full Name	Input	Output
ID	Case ID	Numerical	Numerical
ConY	Confirmed case	N/Y	0/1
ConN	Non-case	N/Y	0/1
AppC	Commercial applicator	N/Y	0/1
AppF	Farmer applicator	N/Y	0/1
AppP	Private applicator	N/Y	0/1
Mn	Month	Numerical	Numerical
Yr	Year	Numerical	Numerical
Yr####	Specific year	N/Y	0/1
ST	Start time	After/before noon	0/1
ET	End time	Before/afternoon	0/1
SnSp	Spring	N/Y	0/1
SnSm	Summer	N/Y	0/1
Dist	Agricultural district	Numerical	Numerical
Ag#	Specific Ag district	N/Y	0/1
UR	Ruralism	Urban/Rural	0/1
PDH	Proximity to dwelling/human	Numerical	Numerical
PDH1	Proximity to dwelling/human	>25ft/<25ft	0/1
PAP	Proximity to affected plants	Numerical	Numerical
PAP1	Proximity to affected plants	>25ft/<25ft	0/1
AV	Applied via	Land/Aerial	0/1
AFA	Applied for agriculture	N/Y	0/1
AFS	Applied for spot spray	N/Y	0/1
AFH	Applied for home use	N/Y	0/1
TCC	Target crop corn	N/Y	0/1
TCS	Target crop soybean	N/Y	0/1
TCB	Target crop blueberries	N/Y	0/1
TCP	Target crop potatoes	N/Y	0/1
TCW	Target crop wheat	N/Y	0/1
PA	Plants affected	N/Y	0/1
PTS	Soybeans affected	N/Y	0/1
PTG	Grapes affected	N/Y	0/1
PTO	Ornamental plants affected	N/Y	0/1
PTF	For-profit garden affected	N/Y	0/1
PTP	Personal garden affected	N/Y	0/1
PDC	Crops damaged	N/Y	0/1
PDP	Personal crops damaged	N/Y	0/1
PDT	Trees damaged	N/Y	0/1
SPDAb	Abnormal damage	N/Y	0/1
SPDAs	Assumed damage	N/Y	0/1
SPDBt	Burnt damage		
SPDDd	Dead damage	N/Y	0/1

SPDDf	Defoliation damage	N/Y	0/1
SPDDs	Discoloration damage	N/Y	0/1
AA	Animals affected	N/Y	0/1
AT	Animal types affected	Other/Livestock	0/1
AD	Animal damage	Other/Assumed	0/1
HE	Human exposure	N/Y	0/1
WSt	Work status	Non-occ/occ	0/1
HSF	Felt spray	N/Y	0/1
HSS	Strong pesticide smell	N/Y	0/1
C24D	2,4-D analyzed for	N/Y	0/1
Q24D	Quantity of 2,4-D found	Numerical	Numerical
CAce	Acetochlor analyzed for	N/Y	0/1
QAce	Quantity of acetochlor found	Numerical	Numerical
CAt	Atrazine analyzed for	N/Y	0/1
QAt	Quantity of atrazine found	Numerical	Numerical
CGly	Glyphosate analyzed for	N/Y	0/1
QGly	Quantity of glyphosate found	Numerical	Numerical
CMt	Metolachlor was analyzed for	N/Y	0/1
CSf	Saflufenacil analyzed for	N/Y	0/1
Cpro	Prothioconazole analyzed for	N/Y	0/1
CPyr	Pyraclostrobin analyzed for	N/Y	0/1
QPyr	Quantity of Pyraclostrobin found	Numerical	Numerical
CTeb	Tebuconazole analyzed for	N/Y	0/1
WS	Wind Speed	Numerical	Numerical
WG	Wind gust	Numerical	Numerical
Tp	Temperature	Numerical	Numerical
RH	Relative humidity	Numerical	Numerical
WS10	Wind speed at 10mph	<10/>10 mph	0/1
WS15	Wind speed at 15mph	<15/>15 mph	0/1
WG15	Wing gust at 15mph	<15/>15mph	0/1
Tp77	Temperature at 77 degrees	<77/>77 degrees	0/1
RH40	Relative humidity at 40%	<40/>40 %	0/1

APPENDIX B: STANDARD OPERATING PROCEDURE

1. Open a case file/summary, Excel spreadsheet, Google Maps, and Weather Underground on a computer.

2. Fill out the following information in an Excel spreadsheet as it appears in the case file/summary or read the case file/summary in full before filling out the spreadsheet.

    a. **Case ID** – Provided by the case.

    b. **Confirmed drift status** – Provided by the case in most instances. If not provided, base entry on consideration of other data.

    c. **Applied by** – Provided by the case.

    d. **Date of alleged spray** – Provided by the case. If there are multiple spray dates, pick either the earliest date or the date when the detected chemical of interest was applied. If no specific date is provided use 0/0/#### or #/0/####.

    e. **Time of application** – Provided by the case. If only one time is provided enter the time as ####-???? or ????-####. If no time is provided then enter *0600-1800.

    f. **Season** – Google search for the last day of spring and summer to determine the season for each case.

    g. **County** – Provided by some cases. Google search the city for the county if not provided.

    h. **Ruralism** – Use Google maps and enter the address of the incident. Consider a location urban if there are suburbs or the presence of an economy. Consider a location rural if there are only one or two residences surrounded by cropland.

    i. **City** – Provided by the case. If exposure happened on a roadway or to a crop field not near the residence, use Google maps to determine the closest city.

j. **Address** – Provided by the case. If exposure happened on a roadway or to a crop field other than at the complainant's residence, use Google maps and enter a crossroad or a house nearby.

k. **Proximity to dwelling/human** – Provided in some cases. Use Google maps and center over the complainant's address. If the location of the treated land is given, use the measurement tool to center one end over the house and the other end at the end of the treated land.

    i. If a person was sprayed and a location is provided, place one end of the tool over that location and the other at the edge of the treated field.

    ii. If no information is given on the location of the treated land, pick a field close to the house and assume it was treated.

l. **Proximity to affected plants** – Provided in some cases. Use Google maps and center over the complainant's address. If the location of the treated land is given, use the measurement tool to center one end over the affected plants and the other end at the edge of the treated land.

    i. If no information is given on the location of the treated land, pick a field close to the house and assume it was treated.

    ii. If the complaint does not concern plant damage, then enter N/A.

m. **Application type 1** – (land/aerial) Provided in some cases. If not explicitly stated, use the other data about the case and make an assumption.

n. **Application type 2** – (Ag/spot spray/right-of-way) Use other data about the case to determine what the application was for.

o. **Target crop** – Provided in some cases. If the crop is not explicitly stated, Google search the pesticides applied to see if it is only used on one type of crop. If it can be used on both soybeans and corn, then label as unknown.

p. **Plants affected** – Based on whether damage was noticed by either the complainant or the investigator.

q. **Plant categories affected** – Provided by the case.

r. **Plant types damaged** – Provided by the case.

s. **Signs of plant damage** – Provided by the case.

t. **Animals affected** – Provided by the case. Choose no if no animals are mentioned.

u. **Animal types affected** – Provided by the case. Choose unknown if no animals are mentioned. Sometimes able to see livestock or horses on Google maps.

v. **Animal damage** – Provided by the case.

w. **Human exposure** – Provided by the case. Based on complainant's narrative of exposure and not on whether any chemicals were or were not detected.

x. **Work status** – Based on whether the complainant was working at the time of the incident. Not based on whether there was human exposure reported.

y. **Human reported symptoms** – Provided by the case.

z. **Chemicals and chemical amounts** – Provided by the case.

aa. **Weather data** – Provided in some cases. Use Weather Underground to fill in missing data by date and time of application.

3. Repeat for each case.

APPENDIX C: SURVEY OF FARMERS

1) ID
2) Age, gender, and ethnicity
3) Home state
4) Since 2010, have agrochemicals (e.g., pesticides) drifted onto your property or into your work area?
    a. Yes/No
5) Was anything harmed due to the off target drift?
    a. Crops/animals/people
    b. Explanation
6) Did you report it to your state's Department of Ag?
    a. Yes/No
    b. If no, why not?
7) Do you know how to report drift complaints in your state if an incident occurs?
    a. Yes/No
8) How would you prefer to report a case of pesticide misuse?
    a. Call/online/both/other
9) What additional pesticide materials or programs should be available for your use?
10) Feel free to include any additional information on the back.